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Single values for an organic soil.

Peaty soils are very rare in Australia, but a typical range of such soils from Australia's sub-Antarctic dependency, Macquarie Island, afforded interesting material for the attempt to assess the contribution to the single values by organic matter itself. Apart from the peat, the mineral matter of the soil consisted in the main of sandy material with very little clay. The range of organic matter content was from 10 to 70 per cent. The data obtained are plotted in Fig. 2, and the linear relationship between the moisture equivalent and the organic matter content is well brought out. This enables the probable moisture equivalent of the organic matter itself to be calculated with a substantial degree of precision and a value of 132 to be obtained. The corresponding

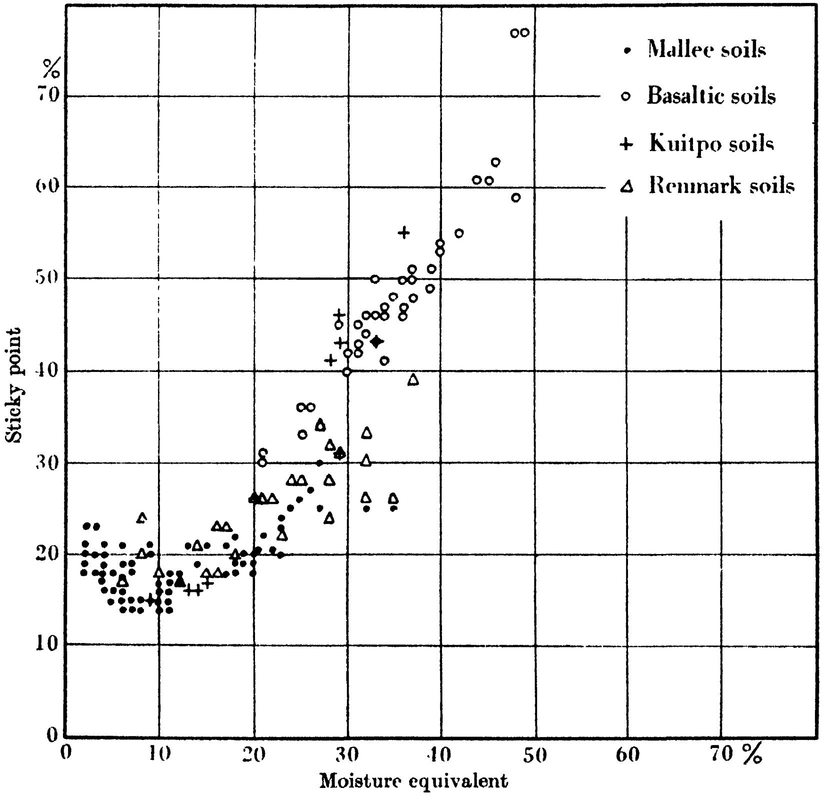

Fig. 1. Showing the relationship between the sticky points and moisture equivalents of four groups of Australian soils.

value for the sticky point, being much more subject to personal errors of estimation, is more difficult to assess but may be expected to be in the neighbourhood of 350, which is of the order of magnitude of the value estimated for organic matter by Keen and Coutts.

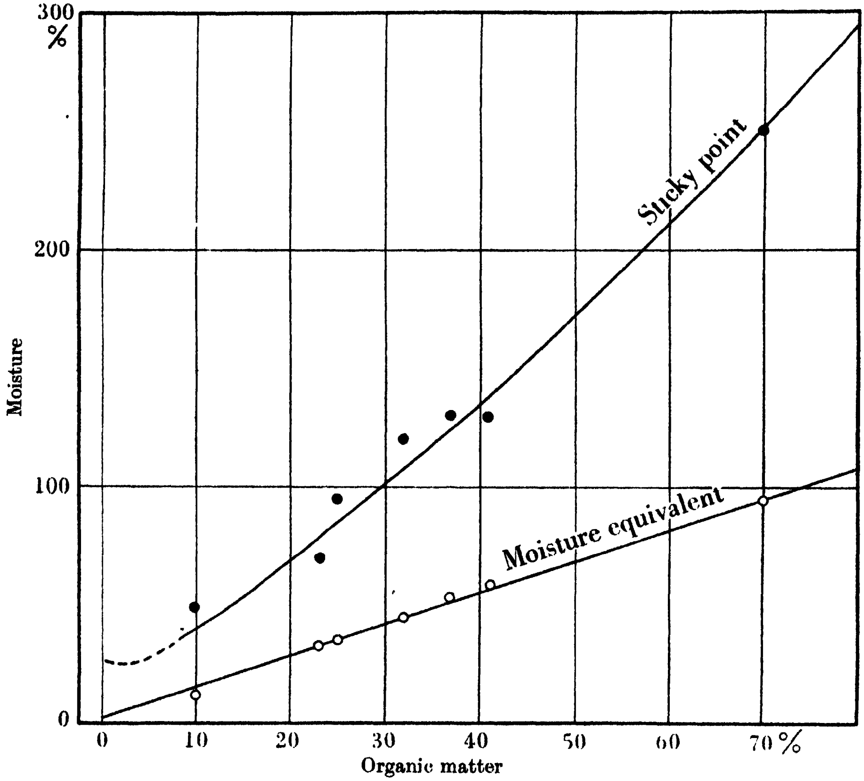

Fig. 2. Showing the relationship between the organic matter content and the sticky points and moisture equivalents of soils from Macquarie Island.

Statistical examination of moisture equivalent data.

The additive character of the moisture equivalent suggested by previous workers and well brought out in the case of the Macquarie Island soils mentioned above, was confirmed by a series of examinations of soil-sand mixtures and of one clay-sand mixture. In the case of five of the soil groups, therefore, assuming such a linear relationship, the regression equations were calculated relating the moisture equivalent to the proportions of silt, clay and organic matter in these soils. The range of data used in calculating the regression equations is given in Table I.

Table I. *Range of mechanical analytical data and moisture equivalents used in calculating regression equations.*

		Mean values				Range of values			
Soil group	No. of samples	Silt %	Clay %	Organic matter %	Moisture equiv. %	Silt %	Clay %	Organic matter %	Moisture equiv. %
Merbein	18	17·2	27·3	—	21·6	12–24	19–39	—	16–35
Mallee	94	3·7	10·8	0·9	9·0	0–16	1–45	0·1–2·4	2–27
Kuitpo	20	20·5	25·5	2·7	22·5	7–36	5–76	0·3–8·8	8–36
Basaltic*	35	16·4	59·2	5·1	34·3	6–29	32–83	1·1–14·7	25–48
Basaltic†	25	21·0	42·4	5·3	35·2	11–33	20–64	0·9–29·6	21–49

* Red loams. † Miscellaneous podsolic soils.

The constants of the regression equations, themselves of the form:

$$\text{M.E.} = a + b_1 \text{ silt} + b_2 \text{ clay} + b_3 \text{ organic matter},$$

and the multiple correlation coefficients are given in Table II.

Table II. *Regression and multiple correlation (R) coefficients between the proportions of international silt, clay and organic matter and the moisture equivalent of groups of Australian soils.*

Soil group	a	Silt	Clay	Organic matter	R
Merbein	2·8	0·288	0·516	—	0·873
Mallee	0·4	−0·031	0·696	1·296	0·977
Mallee	0·4	—	0·692	1·220	0·973
Kuitpo	1·6	0·376	0·386	1·272	0·997
Basaltic*	1·9	0·271	0·374	1·144	0·766
Basaltic†	6·2	0·322	0·410	0·900	0·695

* Red loams. † Miscellaneous podsolic soils.

The most striking thing to be observed in Table II is the very high multiple correlation in the case of the Kuitpo soils; in this group in no case did the value of the calculated moisture equivalent depart from the observed values by more than one unit; of the twenty soils, five gave identical values; nine gave calculated values one unit above and six one unit below the observed value. In this particular case the samples were all selected from a relatively restricted area of a few square miles of related soils falling into five distinct types. The mallee soils which also afford a high value for the multiple correlation coefficient were drawn from quite a large area. The least satisfactory multiple correlation was in the case of the miscellaneous group of basaltic soils which were collected over a considerable range of local conditions; while in the case of both sets of basaltic soils the correlations must be regarded as significant, the precision required in the application of the moisture equivalent as a texture index for soil survey purposes demands a rather more exact regression equation.

An examination of the data in Tables I and II indicates that the partial regression coefficient for silt is roughly proportional to the mean silt content in each group, while the coefficients for clay and organic matter are inversely proportional to their respective means. Whether this is of any significance it is somewhat premature to discuss. The values for the clay fraction can certainly be explained in the light of existing knowledge regarding the chemical nature of the clays in the various groups. The Merbein clays tend toward some degree of sodium saturation, but contain from 17 to 50 per cent. of calcium carbonate. The clays of the selected mallee soils are free from calcium carbonate but show varying degrees of sodium saturation. The Kuitpo clays are all podsolic in character, while the basaltic red loams are very permeable in the field and possess very little plasticity. The calculated values for silt agree quite well with an experimental value of 33·1 per cent. for silt separated from the soil at the Waite Institute. The absence of contribution by the silt of the mallee soils is more difficult to understand. These mallee soils rarely contain appreciable quantities of silt, and whether the absence of effect is due to some inherent property of low values or is purely a statistical accident, is difficult to determine.

Sticky points.

Previous investigators of the relationships between the mechanical analysis of the soil and its sticky point have in general assumed a linear relationship between the clay or colloid content and the sticky point, a relationship which could be extrapolated back to the clay free soils at a value of 16 per cent., representing the approximate pore-space value of the sand-silt framework of the soil.

A graphical examination of the data from the range of the mallee soils, with a considerable proportion of soils with low clay values, revealed the fact that when the clay content of the soil was less than about 10 per cent. higher values for the sticky point were obtained. A number of results for a group of soils with the same clay percentage showed, however, rather wide variations, but on averaging for each group of soils containing the same clay percentage the relationship between the sticky point and the clay content of the soil was found to follow the relationship expressed by the lower curve in Fig. 3. Further confirmation was obtained by preparing mixtures of a fine sand (60–80 mesh) with a sticky point of 29 per cent. with a clay with a sticky point of 70 per cent. separated from a group of Renmark soils. The sticky points obtained in the case of these mixtures are shown in the upper curve of Fig. 3. The general relationship implied can best be discussed by reference to Fig. 4 where the conditions are generalised. The line *OS* represents the contribution to sticky point by the clay content of the soil. The line *AC* represents the contribution to pore space by the non-colloid framework of sand and silt. The pore space corrected for the volume of the clay follows the line *AD*, while that corrected for the volume of the clay at its sticky point follows the line *AE*, so that the sticky point might be expected to follow the line *AES* if only the pore space and the clay content were concerned. Actually the general trend of the sticky point is *AFS*, owing to the fact that the non-colloid framework readily loses its cohesion with increasing amounts of clay.

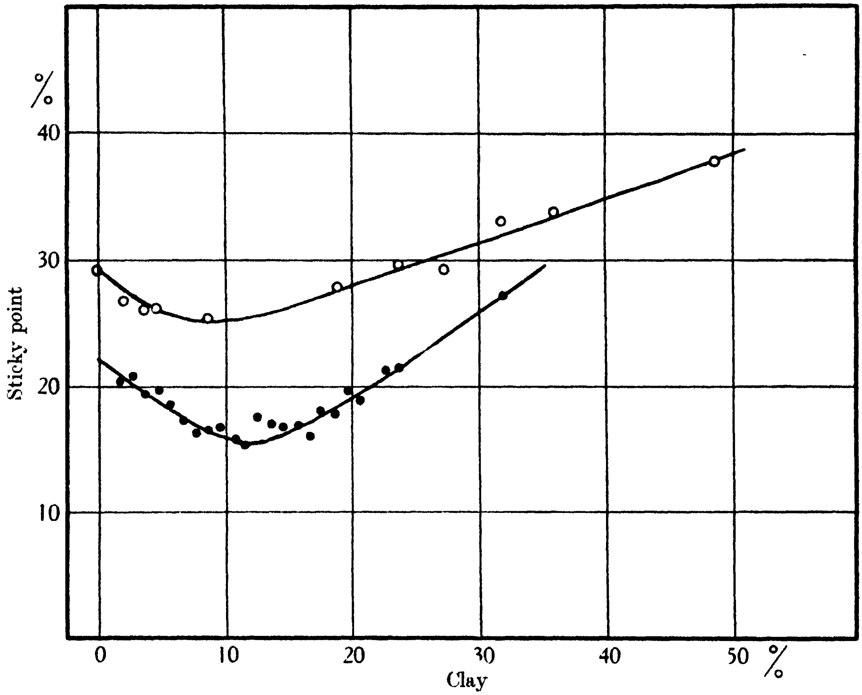

Fig. 3. Showing the relationship between the clay content and the sticky points of soils. The upper curve relates to a mixture of a clay (sticky point = 70 per cent.) with a fine sand (sticky point = 29 per cent.). The lower curve averages the data for a large number of South Australian mallee soils.

The assumption that the pore space contribution by the sand-silt fractions is approximately the same for all soils is not suggested by the trend of the two curves in Fig. 3, and on this account a number of sand-silt mixtures were prepared and the sand-silt fractions of a number of soils were separated by decantation of the clay after the usual preliminary acid and peroxide treatment.

The sticky points and moisture equivalents for a series of such sand-silt mixtures are illustrated in Fig. 5 *a* and *b*. The highest pore space values are naturally obtained with pure fractions, but a value as low as 12 per cent. is obtained with one of the mixtures, while other evidence from our records indicates that values at least as low as 8 per cent. are possible.

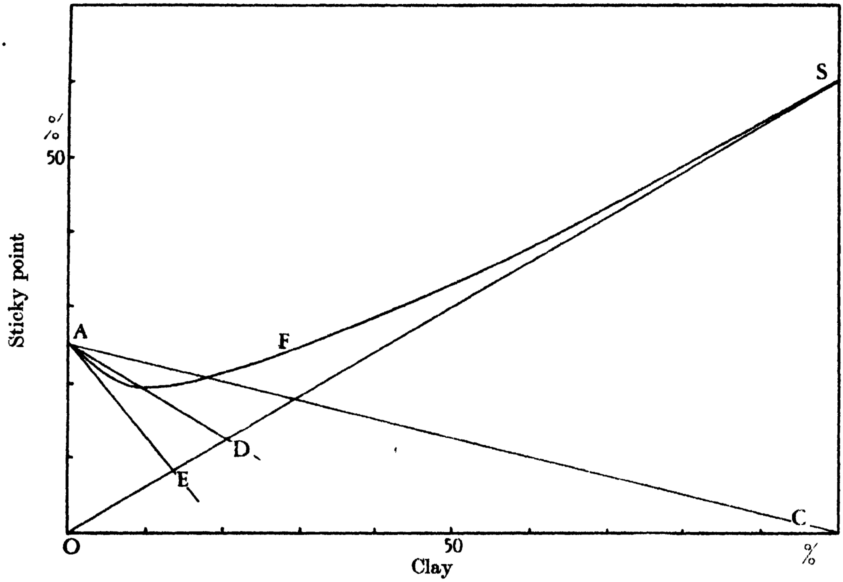

Fig. 4. Illustrating the probable ideal relationship between the clay content of a soil and its sticky point.

The pore space of mixtures of particles of different sizes has been discussed from a general point of view by Manegold, Hofmann and Solf (1931) and has received experimental treatment at the hands of Westmann and Hugill (1930). These latter authors determined the pore space for systems of single-sized particles and for systems of two-sized and of three-sized particles respectively. With suitable mixtures of three sizes of particles with large diameter ratios, the amount of pore space is materially reduced, a minimum possible value of 5·4 per cent. having been calculated. In many respects the data of these latter authors closely parallel those given in Fig. 5 *a*.

An inspection of the data for some of the soil groups investigated suggests that the effect of this non-colloid framework persists up to clay proportions of at least 15 or 20 per cent., and that a relatively high value for sticky point is very frequently associated with a high pore-space value for the clay-free fraction.

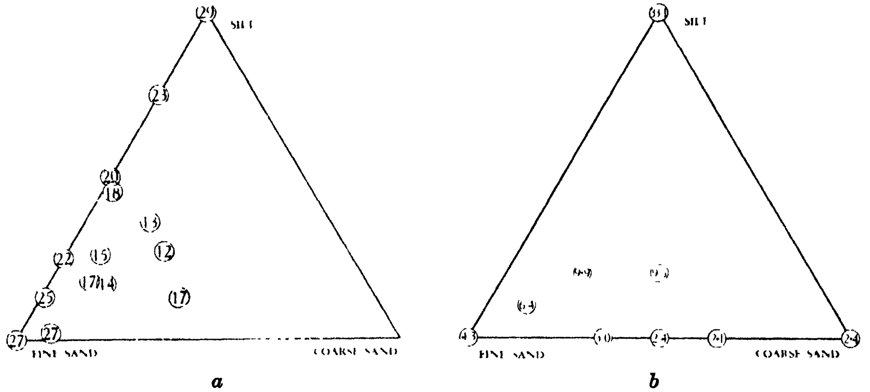

Fig. 5. *a*, illustrating the experimental values for sticky points obtained with mixtures of coarse sand, fine sand and silt. *b*, illustrating experimental values for moisture equivalents with some mixtures of sand and silt.

The influence of the relative proportions of particles of various sizes on the pore space is probably also reflected in the moisture equivalent and is suggested in the values for coarse sand and fine sand mixtures in Fig. 5 *b*. Thomas and Harris (1926) in their work on moisture equivalent point out that with silt particles of 0·01 mm. diameter, the pore space remains completely filled in spite of the high gravitational field. Under these circumstances, one might expect a closer parallelism than is normally the case between the moisture equivalent and the sticky point.

Effect of replaceable bases.

All previous work on the effect of replaceable bases on moisture equivalents indicates that the effect of replacement of some of the natural bases of the soil by sodium or potassium increases the value of moisture equivalent appreciably. In many natural soils with high proportions of replaceable sodium it is in fact almost impossible to secure a true equilibrium point. Most of this previous work has been carried out with soils treated with a salt solution and then washed free from this salt—leaving a soil not necessarily completely saturated with sodium. In the present work some attempts have been made to determine the effect of the degree of base saturation on the single value, and for this purpose a quantity of base-free soil was prepared by treating one of the Renmark soils, an intractable clay loam, with $N/20$ hydrochloric acid and subsequently washing. To this acid-treated soil were then added varying amounts of sodium, potassium and calcium hydroxides, and the moisture equivalents were determined. Owing to the difficulties in securing true equilibrium values, sand dilutions were used, and the values extrapolated to the undiluted soil. The original soil had a moisture equivalent of 27. The results obtained are summarised in Table III.

Table III. *Estimation of moisture equivalent on soils containing replaceable bases in varying amounts.*

Sodium			Potassium				Calcium	
Mg. equiv. per 100 gm. soil	*p*H	Moisture equiv. %	Mg. equiv. per 100 gm. soil	*p*H	Moisture equiv. %	Sticky point	Mg. equiv. per 100 gm. soil	Moisture equiv. %
0	3·4	25	0	3·4	25	—	0	22·8
5	5·1	36*	5	4·3	26*	25	4·3	25·5
10	5·6	57*	10	4·9	28*	26	8·5	25·1
15	7·3	Not determinable	15	6·0	38*	26	17·1	25·7
20	9·5		20	8·9	43*	23	25·6	25·5
25	10·6		25	10·2	34*	23	29·8	25·6
30	10·8	49*	30	10·5	31*	25	—	—
35	10·9	45*	35	10·6	30*	27	—	—

* Extrapolated values.

From the *p*H values one can assume that the soil might be expected to be in equilibrium under natural conditions with 20–25 mg. equivalents of base present. The large effect of sodium, a smaller effect of potassium and the negligible effect of calcium is to be noted. Of particular interest are also the sticky-point values for the potassium soil, which have been affected but little by the treatment and if anything in a direction reverse to that of the moisture equivalent. The highest base values were also associated with free amounts of carbonate, up to 9·3 mg. equivalents being present in the case of the 35 mg. equivalents of sodium, so that the lower values for the moisture equivalent with these higher base saturations may be in part a salt effect.

GENERAL DISCUSSION AND SUMMARY.

The experience with the present range of Australian soils confirms in general previous findings regarding the additive character of the moisture equivalent, and excellent multiple correlations between the silt (0·02–0·002 mm.), clay (less than 0·002 mm.) and organic matter and the moisture equivalent are likely to be found if the statistical examination is restricted to a closely related group of soils. The moisture equivalent contribution of organic matter would appear to lie in the neighbourhood of 130 per cent. for the three most reliable cases examined (132 for peaty soils, 130 for mallee soils, 127 for podsols). The clay contribution is much more variable and accounts for the relatively low multiple correlation obtained with the basaltic soils where the largest discrepancies between observed and calculated values can generally be related to the clay fraction.

For soils with appreciable quantities of exchangeable sodium the moisture equivalent values are high and may be difficult of actual determination. In many such cases possibly a standard technique might be developed in which such soils could first be treated with calcium chloride solution and subsequently washed prior to the determination. Where the determination itself has some special interest probable values may be frequently obtained by extrapolation from the results obtained after mixing with sand.

The values for sticky point are closely related to those for moisture equivalent only in straightforward cases. This is probably due to the fact that the moisture equivalent values for normal calcium-hydrogen clays are probably very close to the sticky points for the same material, whereas the organic matter appears to contribute proportionately much more to the sticky point than it does to the moisture equivalent. Perfect correlation might possibly be expected in the case of a range of soils where the organic matter and clay contents were correlated, and where the colloid content of the soil was above about 15 per cent.

Apparently also the moisture equivalent is much more affected by the proportion of replaceable sodium in the exchangeable bases than is the sticky point and this reduces the correlation between the two single values. Such a case is to be noted in the Renmark group of soils (see Fig. 1). The contribution to the sticky point by the non-colloid fraction is much more variable than has frequently been assumed and depends on the relative proportions of coarse sand, fine sand and silt, values ranging from 29 to 12 per cent. having been observed. As the amount of colloidal material in the soil increases the first effect is the filling up of the pore space associated with a falling sticky point; when the amount of colloidal material reaches the equivalent of about 10 per cent. of clay the sticky point begins to rise in proportion to the colloidal content. The influence of the original pore space may frequently be traced with soils containing as much as 40 per cent. of clay although the relationship is difficult to express quantitatively without further data.

It would appear probable that when the full interrelationships between these two single values and the mechanical analysis has been worked out for a group of closely related soils in association with a soil survey, the two values alone or in combination may be able to throw considerable light on the physical properties of any soil from within this group.

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THE DECOMPOSITION OF GREEN MANURES IN SOIL[1].

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(With Eleven Text-figures.)

THE decomposition of green manures in soil has been very extensively studied, but most of the work has been done mainly to measure the rate of formation of the end products of decomposition. The evolution of carbon dioxide has been used by many workers as a criterion for the decay of organic matter. The production of ammonia and the ultimate accumulation of nitrates have been utilised by others to measure the rate of decomposition. Neither of these measurements, however, supplies precise information concerning the processes that govern the liberation of plant nutrients in an available form.

When a green manure is turned under, the micro-organisms present in the soil break down the complex plant material into simpler substances, part of which they consume for building their body tissues, leaving the rest as by-products. The decomposition of a plant material is, therefore, controlled by the organisms that exist in the soil and the environmental conditions under which they function on the one hand, and by the type and variety of the chemical complexes, of which the plant is composed, on the other.

In the present paper the decomposition of green manures in soil under laboratory conditions has been followed by determining periodically the changes taking place in the various plant constituents, such as the carbohydrates and allied products (Series I) and the nitrogen transformations (Series II).

SERIES I.

Experimental.

Four substances—young tares, young mustard, sugar-beet tops and mature mustard—were used. All the materials were rapidly dried at 55–60° C. and finely powdered. The light sandy soil employed was obtained from the headland of one of the green manure experimental fields at the Woburn Experimental Station. It was air dried and passed through a 1 mm. sieve. Each material was added to the soil at the rate of 5 per cent. on the air-dry basis, and water was carefully mixed in to bring the water content of the whole to about 15 per cent. The mixture was put into shallow Petri dishes and incubated at air temperature in a room that was not subject to great fluctuations of temperature. The dishes were kept loosely covered with other Petri dishes of the same size to exclude dust and to reduce evaporation, while allowing free access of air. The loss of moisture was made up very frequently and the samples were aerated by stirring. Separate samples were incubated for the different stages of decomposition. Five sets of soil samples were laid out in this way, one for each of the four green manures and the fifth for the soil alone, which served as a control.

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[1] This paper is an abridged form of the thesis approved for the Degree of Doctor of Philosophy in the University of London.

The composition of the green manures as analysed by the methods outlined below is given in Table I. The same determinations, with the exception of lignin and ether extract, were made on the decomposing mixtures.

(1) *Total organic matter.* This was estimated by the loss of weight on ignition.

(2) *Water-soluble organic matter.* An aliquot quantity of the filtrate, representing 1 gm. of the material, obtained by shaking with 100 parts of water for 1 hour, was evaporated to dryness and the loss of weight on ignition was taken as water-soluble organic matter. In the case of soil, 25 gm. were shaken with 125 c.c. water and 50 c.c. taken for evaporation. The ash obtained from this determination was taken as soluble mineral matter.

(3) *Ether extract.* 1 gm. of the substance was extracted with ether in a Soxhlet extractor; the extract was evaporated and the residue weighed.

(4) *Total furfuraldehyde.* This was determined by the usual method of distillation with 12 per cent. HCl and precipitation with phloroglucinol. 20 gm. of the soil were used for the determination.

(5) *Cellulose.* Cellulose was determined by the method described elsewhere (2).

(6) *Lignin.* Lignin was determined by the Schwalbe method as described by Norman (4).

(7) *Nitrogen.* By the Kjeldahl method.

(8) *Soil reaction.* pH values were determined by the quinhydrone method.

Table I. *Chemical composition of the green manures and of soil, expressed on* 100 *gm. dry matter.*

	Young tares	Young mustard	Sugar-beet tops	Mature mustard	Soil
Total organic matter	66·60	73·62	81·57	90·81	2·920
Water-soluble organic matter	11·65	22·40	40·20	19·40	0·025
Water-soluble mineral matter	5·35	8·00	7·00	3·70	0·016
Ether extract	2·24	2·43	1·90	1·14	—
Total furfuraldehyde	5·45	6·40	6·65	12·10	0·089
Cellulose	9·71	9·01	7·39	23·32	0·060
Lignin	12·57	13·76	7·38	20·90	—
Nitrogen	3·70	3·65	2·74	1·52	0·114
Potash (K_2O)	2·90	3·85	5·98	—	—

Results.

The decomposition undergone by the various constituents of the green manures is shown in Figs. 1–4. The figures represent the percentage loss of each constituent. They were obtained by subtracting the amount of each of the constituents present in the control soil at the different periods of incubation from those present in the manured soils calculated back to the original material. The percentage loss was worked out therefrom.

Discussion.

There is a very rapid fall of soluble organic substances during the first 4–8 days in the case of all the four plant materials. The rate then falls off and there is very little decomposition after 25 days. Mature mustard contains almost as much soluble organic material as young mustard, yet it loses appreciably more, especially during the first week. The rapidity of decomposition of hemicelluloses as judged by the loss of total furfuraldehyde is about the same in the case of young tares, young mustard and sugar-beet tops. Mature mustard, however, decomposes more slowly though it contains a greater abundance of this group of substances. This is because it contains less soluble nitrogenous compounds than the other three (Series II).

There is no appreciable loss of cellulose during the first 4 days, whereas a considerable amount of the soluble organic matter and hemicelluloses decomposed during that time. The easy and rapid availability of these two latter classes of compounds to the micro-organisms during the opening stages of decomposition is thus evident. A great loss of cellulose takes place during the next 4 days in the case of young tares, young mustard and sugar-beet tops. The rate of disappearance of cellulose in mature mustard is slower on the whole. The comparatively slow

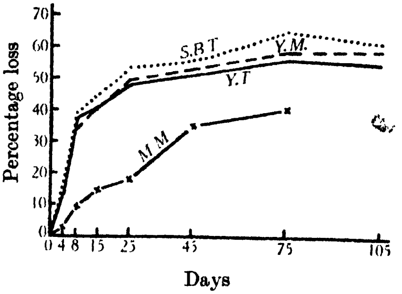

Fig. 1. Decomposition of total organic matter.

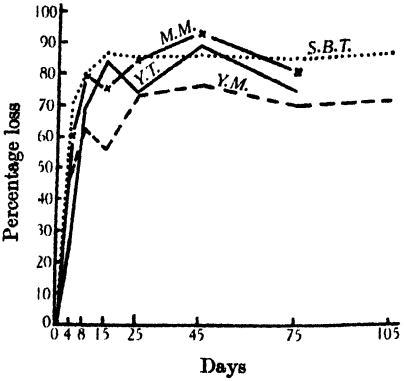

Fig. 2. Decomposition of soluble organic matter.

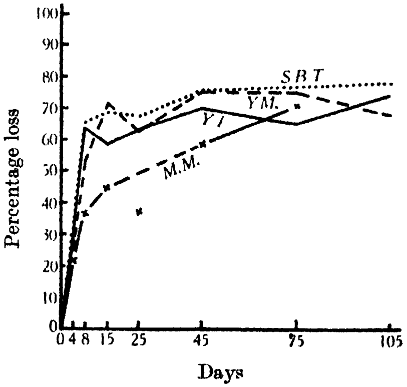

Fig. 3. Decomposition of total furfuraldehyde.

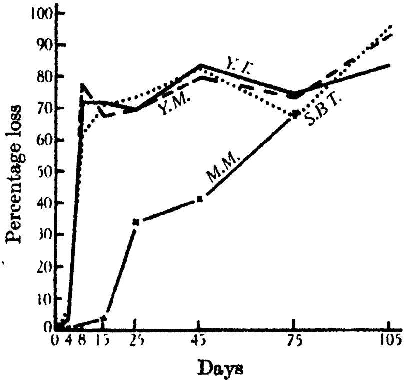

Fig. 4. Decomposition of cellulose.

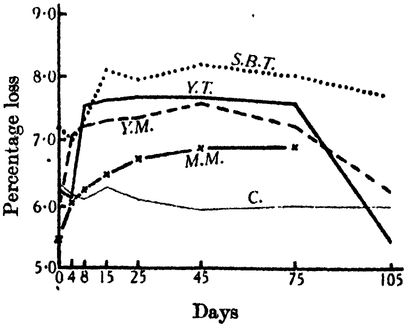

Fig. 5. Soil reaction.

S.B.T. Sugar-beet tops. *Y.M.* Young mustard. *Y.T.* Young tares. *M.M.* Mature mustard. *C.* Control.

decomposition of cellulose in mature mustard is principally due to the high content of lignin which, by virtue of its encrustation on the cell walls, acts as a barrier to the utilisation of cellulose by micro-organisms. But, in view of the fact that the proportion of lignin to cellulose is much higher in the case of young tares, young mustard and sugar-beet tops than in mature mustard, it seems that the rapid availability of cellulose in the young plant materials is only apparent. It is because of the low cellulose content of these three plant materials as compared with their available nitrogen contents that almost the whole of that cellulose is required and used up by the micro-organisms. In other words the amount of available nitrogen in these three plant materials is more than sufficient to balance the total available carbohydrate, viz. the sugars, the hemicelluloses and cellulose. The reverse is true in the case of mature mustard, so that, after the first rapid removal of the soluble carbohydrates together with the soluble nitrogenous compounds, the other carbohydrate compounds decompose slowly as the rest of the nitrogenous substances become available. This is more clearly shown in the data presented in Table II. The sum of the soluble carbohydrates (soluble organic matter – total soluble N × 6·25), hemicelluloses (total furfural × 2), and cellulose is taken as the total available energy material and the sum of the total water-soluble nitrogen plus the nitrogen hydrolysed by H_2O_2 (Series II) is taken as the total available nitrogen. It has been shown that for each part of nitrogen assimilated, fifty to sixty parts of cellulose (12) and twenty to forty parts of hemicelluloses (13) are decomposed. Taking an average of these figures, the energy material that would be required for the total amount of available nitrogen present in each plant material is calculated and shown in the last column of the table.

Table II.

	Total energy material present	Total available nitrogen present	Energy material equivalent to available nitrogen (calculated)
Young tares	26·1	2·47	105
Young mustard	37·6	2·13	90
Sugar-beet tops	54·5	1·74	73
Mature mustard	63·7	0·81	34

Young tares, young mustard and sugar-beet tops contain relatively little carbohydrate in proportion to the available nitrogenous compounds present. Hence a very rapid and immediate decomposition takes place.

The total organic matter disappeared less slowly in the case of all the four plant materials than the hemicelluloses, cellulose and soluble organic matter. This is primarily due to the accumulation of the more resistant constituents, chiefly lignin, which does not decompose as readily as the other plant constituents. Lignin was not determined in the decomposing materials, mainly because there is no suitable method for estimating it in a mixture of soil and plant material. The formation of new organic matter in the tissues of the fungal mycelium and bacteria is also a cause of the less rapid decomposition of total organic matter.

These results are in keeping with the findings of Rege (7), Norman (5), Waksman and his associates (13, 14, 15) and others cited by Tenney and Waksman (11). Rege first observed that in mature plant materials pentosans form the principal food material for the micro-organisms. This was later confirmed by Norman, who emphasised the importance of cellulose along with the pentosans as the chief source of energy material for the organisms. He further supported the view of Rege that lignin acts as an inhibitory agent. The work of Waksman and his colleagues showed that the decomposition depends on the nature and age of the plant material. The younger the plant the more rapidly does it decompose. The decomposition is influenced by the type of compounds present in the plant material, some like sugars, hemicelluloses and cellulose being more easily available than the others, *e.g.* lignin, resin and waxes. In confirming the previous work of Hutchinson and Richards (3) they further showed that there is a definite proportion between the amounts of available carbohydrate and available nitrogen for the requirements of the activities of the micro-organisms. Hence plants having a balanced proportion of these two classes of compounds decomposed more rapidly than others.

The nitrogen figures are more fully discussed in the second series of experiments.

The effect of green manures on the soil reaction is well marked (Fig. 5). After a small increase of acidity during the initial stages of decomposition the soil tends to become alkaline and remains so for a major part of the period of incubation. The increase in acidity and then in alkalinity seems to correspond with the production of organic acids from sugars and starches followed by, or simultaneously with, the production of ammonia. The fall in *p*H values during the later stages of decomposition corresponds to the formation of nitrates (Series II). Soil mixed with sugar-beet tops, however, remains alkaline even after nitrification has set in. This is due to the large amount of potash in the sugar-beet tops, which tends to keep the soil alkaline. Other differences in the soil reaction due to the various green manures can also be similarly explained. The reaction of the soil is controlled by two factors: (1) the products of decomposition, viz. the organic acids, ammonia and nitrates, and (2) the liberation of the ash constituents of the green manure. The preponderance of one over the other decides the condition of the soil at any given time. The work of White (16), Stephenson (9, 10) and Smith and Humfield (8) goes to show that the soil becomes alkaline during the early stages of decomposition but becomes acidic later on.

SERIES II.

The second series of experiments was designed to determine the nitrogen changes that take place during the decomposition of the green manures under study. Besides measuring the accumulation of ammonia and nitrates an attempt was made to observe the changes taking place in the potentially available class of compounds other than those soluble in water.

Mixtures of soil plus green manures were laid out in Petri dishes in the same way as in Series I, and samples were taken for analysis at the same intervals but for 65 days only.

The following determinations were carried out:

(1) *Total nitrogen.* Total nitrogen was determined by the salicylic-thiosulphate method to include nitrate nitrogen (1).

(2) *Water-soluble ammonia nitrogen.* A suitable quantity of the soil was shaken with five times its weight of water for 1 hour; an aliquot volume of the clear filtrate representing 20 gm. of the soil was distilled with magnesia and ammonia collected in standard acid.

(3) *Nitrate nitrogen.* Nitrate nitrogen was determined from the same filtrate as the ammonia, the contents of the flask being made up with water and 2-3 gm. of Devarda alloy added.

(4) *Total water-soluble nitrogen.* On another aliquot from the soil extract total soluble nitrogen was determined according to Ranker (6). Total soluble nitrogen minus ammonia plus nitrate nitrogen is taken as water-soluble protein nitrogen.

(5) *Hydrogen peroxide nitrogen.* The action of dilute H_2O_2 was used to determine the potentially available class of nitrogenous compounds. The residue after water extraction was treated with 60 c.c. of a 3 per cent. solution of hydrogen peroxide. After the initial frothing had ceased, it was boiled for 15 min. The extract was filtered through a Buchner funnel, the residue washed and the filtrate made up to a definite volume. An aliquot portion of the filtrate was distilled with magnesia

and another with caustic soda. Each time ammonia was collected in separate quantities of standard acid. The residual soil was then further treated with another 60 c.c. of 3 per cent. hydrogen peroxide and ammonia determined as in the previous case. A third extraction was then made on the residual material and ammonia determined again as before. Thus each sample gave two forms of nitrogen three times in succession.

Assuming that the oxidising power of 3 per cent. hydrogen peroxide, under standard conditions of time and volume, measures the availability of the less easily available class of compounds, this group is sub-divided into two classes: (1) that which would be more easily available; this is measured by the distillation of the extract with magnesia and called "H_2O_2 nitrogen I," and (2) the rest of the nitrogen, which is measured by the difference between the nitrogen evolved by the caustic soda distillation and that by the magnesia distillation. This form of nitrogen is referred to as "H_2O_2 nitrogen II." The nitrogen evolved by the caustic soda distillation is referred to as the "Total H_2O_2 nitrogen."

The green manures were subjected to this system of analysis, the results of which are given in Table III.

Table III. *Different forms of nitrogen in the green manures, expressed on* 100 *gm. dry matter.*

		Young tares	Young mustard	Sugar-beet tops	Mature mustard
1. Total nitrogen		3·70	3·65	2·74	1·52
2. Water-soluble nitrogen					
Ammonia nitrogen		0·096	0·249	0·089	0·049
Nitrate nitrogen		0·096	0·121	0·160	0·034
Total soluble nitrogen		1·18	1·43	1·27	0·60
Percentage of total nitrogen		31·90	39·20	46·30	39·50
3. H_2O_2 nitrogen I	1st extraction	0·460	0·114	0·124	0·029
	2nd extraction	0·226	0·179	0·049	0·032
	3rd extraction	0·051	0·111	0·041	0·019
4. H_2O_2 nitrogen II	1st extraction	0·383	0·102	0·162	0·056
	2nd extraction	0·169	0·133	0·041	0·047
	3rd extraction	0·002	0·064	0·052	0·031
5. Total available nitrogen (2 + 3 + 4)		2·47	2·13	1·74	0·81

It is interesting to note that mature mustard contains relatively as much nitrogen in a soluble form as young mustard. It is the nitrogen soluble in water which, according to Whiting and Richmond (17), is responsible for the early nitrification of plant materials even though they may contain less total nitrogen. Young tares contain considerably more nitrogen oxidised by H_2O_2 both absolutely as well as relatively to the total nitrogen, than the other three plant materials. Looking to the nitrogen oxidised at each of the extractions it will be noticed that young tares and sugar-beet tops liberate a major portion of the nitrogen at the first extraction both as H_2O_2 nitrogen I as well as H_2O_2 nitrogen II. In the case of young as well as mature mustard, however, it is a more gradual liberation.

RESULTS AND DISCUSSION.

The results of the decomposition studies of the four green manures are presented in Figs. 6–11. As the nitrogen liberated by hydrogen peroxide at the three different extractions did not show any noticeable differences, the total of the three extractions is given together. All the results have been calculated on the original dry matter and represent nitrogen present in the soil mixtures at different periods.

The loss of total nitrogen, especially in the case of young tares, young mustard and sugar-beet tops is considerable. A similar loss of nitrogen was noticed in the first series of experiments. It was then not clear whether that loss was actual or only apparent as the nitrogen determinations did not include nitrates. In the present series of experiments, where the total nitrogen was determined so as to include nitrates, the loss becomes actual. It has been shown previously (Table II) that these three plant materials have a very high proportion of total available nitrogen to total energy material. In other words they have a narrow nitrogen-carbon ratio. This accounts for the loss of nitrogen noticed in these experiments.

Similar losses of nitrogen have been observed by other workers. Tenney and Waksman (11) noticed a decrease of total protein during the decomposition of alfalfa which contained 2·58 per cent. total nitrogen. But the more striking experiments are those of Zolcinski and Musierowicz (18, 19) who, while studying the decomposition of lucerne and red clover, noticed large losses of total nitrogen. These are materials both very rich in nitrogen. The present experiments are, therefore, in accord with the results obtained by them.

The opening stage of the decomposition is characterised by a rapid loss of soluble nitrogen during the first 4 days (Fig. 7). During the same time there is an increase in the amount of total H_2O_2 nitrogen (Fig. 10). It seems therefore that the soluble nitrogen is being converted into more complex nitrogenous compounds, very probably the synthesised protein matter of the fungi that are growing very vigorously at that time. A part of the increase in total H_2O_2 nitrogen may also be due to the

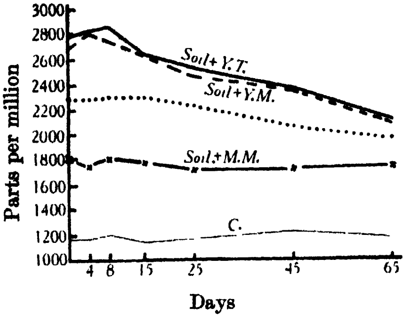

Fig. 6. Changes in total nitrogen.

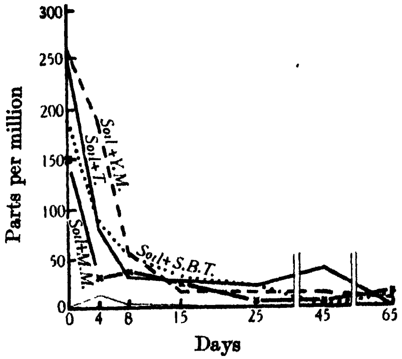

Fig. 7. Changes in water-soluble protein nitrogen.

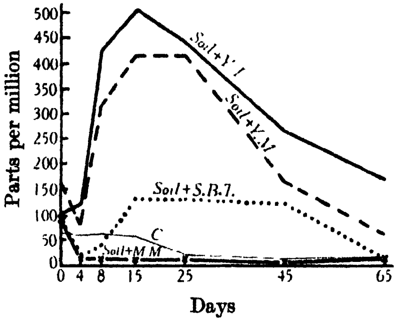

Fig. 8. Changes in water-soluble ammoniacal nitrogen.

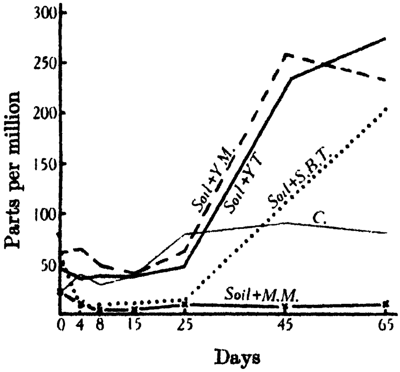

Fig. 9. Changes in nitrate nitrogen.

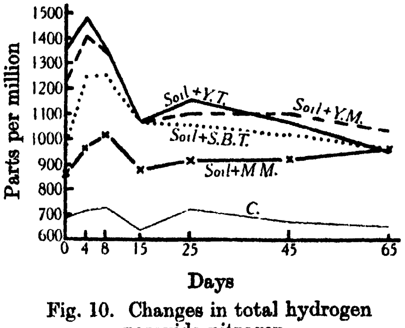

Fig. 10. Changes in total hydrogen peroxide nitrogen.

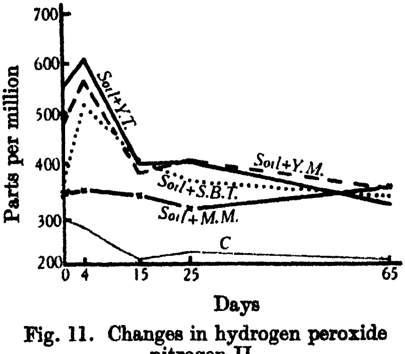

Fig. 11. Changes in hydrogen peroxide nitrogen II.

Soil + Y.T.	Soil + young tares.	*Soil + Y.M.*	Soil + young mustard.
Soil + S.B.T.	Soil + sugar-beet tops.	*Soil + M.M.*	Soil + mature mustard.

C. Control.

breaking up of the more complex nitrogen compounds. After 4 days this class of compounds begins to be broken up again, giving rise at the same time to ammonia. A little later nitrification sets in and nitrates begin to accumulate. The late nitrification is mainly due to the large accumulation of ammonia which checks the activities of nitrifying organisms for a time. With the increase of nitrates there is a sharp fall of ammonia and this goes on to the end of the period of incubation. At the same time the fall of the nitrogen oxidisable by hydrogen peroxide continues though more gradually than before. The water-soluble protein nitrogen remains almost constant at a very low level after the first rapid consumption (Fig. 8).

Mature mustard differs considerably in its chemical composition from the other three plant materials. Hence the nature of changes taking place in its nitrogen is strikingly different. It does not lose any appreciable amount of total nitrogen. There is a small but definite increase in the amount of total H_2O_2 nitrogen after the first 15 days, unlike the other green manures. This increase in nitrogen oxidisable by hydrogen peroxide is very probably due to the activities of the micro-organisms breaking down the hemicelluloses and cellulose which are present in larger quantities in this plant material than in the other three. The lack of available nitrogen is shown by the depression caused in the level of ammonia and nitrates below that of the control soil. In other words the micro-organisms are utilising the soluble nitrogen present in the soil for the decomposition of the soluble carbohydrates and the hemicelluloses. Hence there is no accumulation of ammonia nor of nitrates over a period of 65 days.

To sum up, the results presented in this series of experiments show that when a green manure rich in nitrogen is incorporated with the soil, large losses of nitrogen take place. The loss of nitrogen depends not only on the amount of total nitrogen contained in the green manure but also, and more especially, on the amount of nitrogen that is easily available. The greater the amount of total and available nitrogen the greater is the loss of nitrogen likely to occur. The results also give an insight into the nature of the changes taking place in the nitrogenous compounds of the green manures. The soluble nitrogenous compounds are attacked first and are metabolised into a more complex form of protein. This protein together with that existing in the green manure is then attacked and converted first into the less complex forms (*e.g.* water-soluble) and subsequently or simultaneously into ammonia and nitrates. Since a green manure rich in nitrogen is almost always comparatively poor in carbohydrate compounds, there is the risk of a part of the ammonia being lost.

SUMMARY.

Four plant materials of widely different origin and age were used as green manures mixed with soil for decomposition studies under laboratory conditions.

Provided the conditions of temperature, moisture, aeration, and micro-flora, are optimal, the decomposition depends upon the chemical constituents of the plant materials. It is shown that the soluble carbohydrates, hemicelluloses and cellulose are the compounds mainly responsible for the loss of total organic matter during decomposition.

Plant materials containing a balanced proportion of available carbohydrate compounds to available nitrogenous compounds decompose rapidly. Those containing excess of nitrogenous compounds decompose more rapidly and those containing excess of carbohydrate compounds decompose less rapidly. This is true in all cases whether the plant material is a legume or a non-legume. Young plant materials by virtue of their abundance of available nitrogenous compounds decompose more quickly than mature tissues.

When comparatively young plant materials are used as green manure, there is the danger of a loss of nitrogen, the loss depending upon the amount of total and available nitrogen this contains. Not only do they lose nitrogen but they decompose very rapidly, with the result that nitrates accumulate soon after burial. Unless the succeeding crop is sown sufficiently early to utilise these nitrates, they are likely to be lost through leaching under field conditions.

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THE USE OF THE GLASS ELECTRODE IN SOIL REACTION AND OXIDATION-REDUCTION POTENTIAL MEASUREMENTS.

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(With Three Text-figures.)

Although the quinhydrone electrode is generally recognised as the most convenient method for reaction measurements of soil suspensions, it is liable to give erroneous results in many common kinds of soil (1, 2, 3). It is therefore of interest to ascertain the value of alternative electrodes which can serve for independent check measurements, even though they should prove to have no advantage over the quinhydrone electrode where this is known to be reliable. For this reason the following results of experience with the glass electrode are placed on record.

Full discussions of the glass electrode are available in several textbooks, notably that of Clark (4), as well as in a series of papers of MacInnes and co-workers, and it is therefore unnecessary to present the underlying theories or practical details, except in so far as they relate to soils.

The theory of the glass electrode was put forward as early as 1909 by Haber and Klemenziewicz (5), but it was not until 1925 when Kerridge (6) improved the design that the electrode came into more general use, especially for biochemical purposes. More recently the introduction of special valve amplifiers, capable of operating in systems with such high resistances as that provided by the glass membrane, has made it possible to dispense with the troublesome quadrant electrometer and the careful shielding imperative in earlier designs. In the above-mentioned series of papers by MacInnes and Doles (7, 8) on the use of the glass electrode for *p*H measurements of a high degree of accuracy, it was shown that the glass electrode may be regarded purely as a hydrogen electrode, provided the salt concentration is not too high. Its specific advantages may be summarised as follows. It is independent of oxidants and reductants and has a low salt error. Further, it causes no alteration in the system under measurement. It is thus free from the poisoning effects, the loss from carbon dioxide, and the reduction of oxides of manganese and other materials which may occur when the hydrogen or the quinhydrone is used for soils. The reproducibility of measurements is much greater than with metallic electrodes as *e.g.* the antimony electrode.

*p*H MEASUREMENTS ON SOIL SUSPENSIONS.

The electrical measuring apparatus was one designed by Harrison (9) and supplied by Messrs Kay and Co., 4 Holborn Place, London, W.C. 1, in a convenient unit which was used with a simple Cambridge potentiometer. The chief feature of this device is a specially designed amplifying valve — an Electrometer Triode from Messrs Philips Lamps, Ltd.—which has so low a grid current that there is no change in anode current due to introduction of resistance into the grid circuit. For measurements on soil suspensions and soil crumbs glass electrodes made by Messrs Dixon of 27 Devonshire Street, W.C. 1, have proved very suitable. The thin glass membrane is in the form of a re-entrant bulb in a stout bulb at the end of a short tube (Fig. 1). This arrangement provides great mechanical strength and easy cleaning. As recommended by Harrison, the glass was made by fusing silica 60 per cent., sodium carbonate 30 per cent., and calcium carbonate 10 per cent. The electrode was supported on the tube of a saturated calomel electrode of the Kerridge type carefully insulated through "Amberoid." All parts of the apparatus were mounted on an earthed copper plate and batteries and vessels containing the soil suspension were placed on large paraffin blocks. No further shielding or insulation proved to be necessary. The glass electrode contained Veibel solution (0·01 *N* HCl, 0·09 *N* KCl). The suspension to be measured was placed in a beaker and stirred by means of the glass electrode so that soil particles settled down inside the thin bulb. To complete the circuit a second Kerridge saturated calomel electrode was placed in the suspension at some distance from the bulb. Diffusion of potassium chloride was prevented by fitting the electrodes with ground-glass caps. The

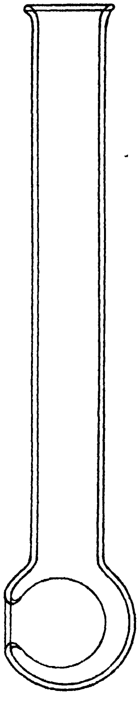


Fig. 1. Length 9·5 cm., diameter of outer bulb 0·9 cm.; diameter of inner bulb 0·6 cm.

"asymmetry" of the glass membrane and calomel electrodes was small (not more than 2 mv.), but in all cases it was eliminated by referring all measurements to a standard solution. Equilibrium was reached within the first 5 min. in soil suspensions.

The difference in hydrogen and glass electrode potentials of buffer solutions varying from *p*H 2·5 to 9·5 was constant within the limits of measurements (1 mv.).

In a series of soil samples selected so as to give the widest possible range of type of soil, country of origin, and reaction (*p*H 3·8–9·1) measurements were so satisfactory that it is not necessary to tabulate typical values. In a series of nineteen soils for which the quinhydrone electrode gave reliable values as shown by independent tests, the mean difference in *p*H by glass and quinhydrone electrodes was +0·01 and the standard error of a single difference was ±0·05. For twelve soils to which the quinhydrone method was not applicable, the mean difference by glass and hydrogen electrodes was 0·00 with a standard error of a single difference of ±0·04.

*p*H MEASUREMENTS ON MOIST SOILS.

The fact that in the glass-electrode method no foreign substance has to be incorporated uniformly throughout the soil suggested the possibility of glass-electrode measurements at lower soil moisture contents than are possible when quinhydrone or hydrogen must be brought into equilibrium with the soil. Crumbs of moist soil, taken directly from the field or prepared by remoistening air-dried soils, were placed in the thin glass bulb and connected electrically to the second calomel electrode by means of a loose mass of similar crumbs. Satisfactory voltage readings corresponding closely to those on suspensions (1 soil:1 water) of the same soil were obtained, provided the soil crumbs were moist enough to wet the glass membrane and establish an appreciable area of intimate contact between soil and glass. For soils below the "sticky point," where there was no such contact, the voltage readings, although constant and reproducible, resulted in *p*H values between 5·6 and 6·2, irrespective of the reaction of corresponding soil suspensions.

These values must therefore be taken to represent the *p*H value of a thin moisture film in equilibrium with the carbon dioxide content of the air and with the glass but not in equilibrium with the soil moisture. Similar results have been obtained by Kahler and Floyd Deeds (10), working in buffer solutions when only parts of the glass film were in contact with the solution.

Table I illustrates these results for a series of air-dried soils moistened with a spray of water and worked up into crumbs.

Table I. *p*H *values by glass electrode on soil crumbs.*

	Moisture as percentage of dry soil			
	10	20	50	100
Millstone Grit soil	5·3	5·3	4·1	4·1
Chernozem	5·7	5·8	6·0	6·1
Rothamsted soil	5·5	6·2	7·5	7·7

Most soils behave as the Millstone Grit soil in Table I. At a moisture content of about 30 per cent. the *p*H value changed rapidly; in this case it fell but in other soils it rose sharply.

A few soils showed a slower change over a wider range of moisture. Two of these are illustrated in Table I. In the highly granulated chernozem there was no sharp point of wetting with increasing moisture content, and in the Rothamsted soil the small fragments of calcium carbonate present may have come into contact with the glass membrane before the mass of the soil crumbs.

From the fact that the glass electrode gives satisfactory results for untreated field soils, moist enough to wet the glass membrane, it should not be concluded that the glass electrode possesses special merits for such work. On the contrary, the quinhydrone electrode may be used at lower moisture contents than the glass electrode, since to establish contact it is necessary to press the mixture of crumbs and quinhydrone on to the electrode; such pressure is not possible with the thin glass membrane.

Table II gives comparisons of glass and quinhydrone electrode measurements on crumbs, and glass electrode measurements on the corresponding soil suspensions for a soil treated with varying amounts of calcium hydroxide, and subsequently air dried and remoistened below the "sticky point." The quinhydrone electrode gives substantially correct but the glass electrode gives erroneous results in the dry crumbs.

Table II. *p*H *values by glass and quinhydrone electrodes on soil crumbs and suspensions.*

	$Ca(OH)_2$ added as mg. eq. %			
	0	1	5	10
Quinhydrone measurements on crumbs	4·4	5·0	—	7·0
Glass electrode measurements on crumbs	5·5	5·5	5·5	6·2
Glass electrode measurements on suspension	4·5	5·1	6·0	7·4

For measurements in soil suspensions the glass electrode provides a useful supplement to older methods with no special merits in cases where the quinhydrone method is applicable. It can, however, be used in solutions of much higher *p*H than the quinhydrone electrode and has the advantage for alkaline soils that no disturbance arises through removal of carbon dioxide, as in the hydrogen-electrode method. It is particularly suitable for measurements on highly oxidising or reducing systems and may therefore be used satisfactorily in soils with active oxides of manganese or iron, or in intensely reducing soils, such as are obtained by waterlogging in the presence of fermentable organic matter. Finally, it may be used in soils treated with hydrogen peroxide, sodium hypobromite, or similar materials.

OXIDATION-REDUCTION POTENTIALS.

Since the metallic electrodes used in oxidation-reduction measurements are readily polarised in all but the simplest systems, and since the potentials in complex systems must be considered in relation to the *p*H value or hydrogen-electrode potential, there is a definite advantage in using the glass electrode for such measurements. Its high resistance ensures that minimal currents shall pass through the system and the absence of added material simplifies the reaction measurements. The oxidation-reduction potentials, however, have proved to be easier to measure than to interpret, and the following results are recorded to indicate the complexity of the phenomena and to offer a warning against the increasingly common practice of drawing deductions from a few isolated measurements, often given without *p*H values.

There is a close formal analogy between the oxidation-reduction potential, measured at a polished platinum electrode in a "poised" system with oxidant and reductant in reversible equilibrium, and the potential of an electrode in equilibrium with both hydrogen gas and a "buffered" system containing a weak acid (or base) and its salt in reversible equilibrium. The potential varies with the ratio of reactants responsible for "poising" or "buffering." It is to be expected that in biological systems the active oxidants or reductants should themselves behave as weak acids or bases and the hydrogen-ion concentration must therefore be used in interpreting the oxidation-reduction equilibrium. In only a few simple cases has it been possible to work out the relationship of the intensity factor or measured potential to the quantity factor or amounts of oxidant and reductant. In the quinhydrone system the oxidation-reduction potential is so closely related to the hydrogen potential that the measurement of this oxidation-reduction potential has become a standard method for the determination of *p*H values. If complex systems like soils contain material analogous to quinhydrone, it is obvious that no oxidation-reduction potential can be of any interest unless made at a measured *p*H value. Clark (4) and his co-workers have studied a great number of organic systems with the object of finding a range of oxidation-reduction indicators but only few of them provide simple relationships. There is little prospect at present of developing for many systems such theoretical relationships as hold for quinhydrone.

The empirical approach has been more successful and useful results have been obtained in biological systems. Thus in standardised media the form of the potential-time curve can serve to characterise groups of micro-organisms or cellular processes, *e.g.* denitrification.

Empirical methods have given valuable results in soil reaction work in spite of the fact that the exact nature of the acidic or basic materials present was unknown, and it might therefore be expected that a similar method could be used in oxidation-reduction measurements. There is, however, the essential difference that though it is possible by addition of alkali or acid to alter the *p*H value of the soil or other system and so study the resulting titration curve, there is no such simple method of altering in a reversible manner the oxidation-reduction potential of a soil or other complex biological system. The *p*H titration curves of soil are determined by the inorganic and organic colloidal fractions of the soil, both of which are relatively stable in nature and amount. If the oxidation-reduction potentials reflected the state of oxidation of the greater part of the iron and manganese compounds or of the organic matter of the soil, they would be of value in studies of soil formation and in connection with drainage and irrigation problems, whilst if they are determined by small amounts of active compounds produced by micro-organisms they would be too variable to be of general value, and it would become necessary to standardise empirical methods which would make the microbiological activity reflect either the reserve of readily oxidisable material or the environmental conditions.

The fundamental and pioneering work on soil oxidation-reduction potentials was carried out by Gillespie (11) in 1920. He studied the changes in oxidation-reduction potentials with time when soils were waterlogged with and without readily decomposable organic matter in the form of carbohydrates, and the potential-time curve in bacterial cultures under controlled conditions. The latter section of his work has been developed greatly through the work by Clark and co-workers, Michaelis and others, but little has been added to the study of soil beyond establishing the fact that soils give definite and reproducible oxidation-reduction potentials under standardised conditions.

MEASUREMENTS OF OXIDATION-REDUCTION POTENTIALS IN SOIL-WATER SUSPENSIONS.

The underlying theory of oxidation-reduction potentials in general may be found in such text-books as those of Clark (1) and Wurmser (12).

If the glass electrode is used as a reference electrode, thus minimising polarisation and allowing simultaneous oxidation-reduction potential and *p*H measurements on the same soil suspension, the cells may be represented as:

Hg | HgCl KCl | Veibel | Glass | Soil suspension | Pt
Hg | HgCl KCl | Veibel | Glass | Soil suspension | HgCl KCl | Hg

The platinum electrodes (1 sq. cm.) were kept perfectly clean and bright. For each measurement two or more were used and the different electrodes usually agreed within 10 mv. The oxidation-reduction potentials (E_h) are given for the platinum electrode in the suspension relative to the normal hydrogen electrode as zero. They are thus positive for most oxidising systems and decrease with increasing reduction and with increasing *p*H.

The suspensions were made up from equal amounts of soil and water, but as the electrodes were always placed in the soil paste the precise soil-water ratio is of little importance. In general, constant and reproducible potentials were obtained within one or two hours and often more rapidly. Measurements in a nitrogen atmosphere gave the same results for the oxidation-reduction potentials as when air was present, a result which confirmed earlier measurements on soils by Herzner (13). The measurements quoted later were obtained with air present.

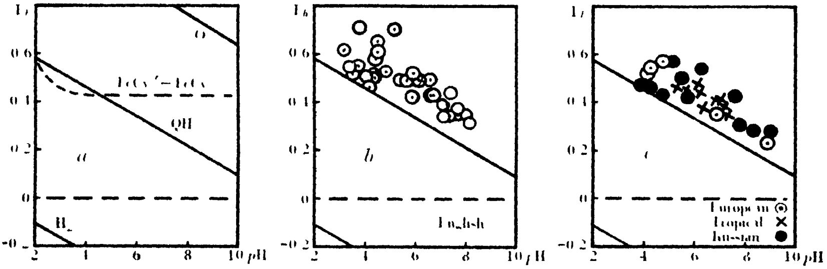
The oxidation-reduction potentials of a wide range of English, European and tropical soils generally tended to follow the *p*H values.

A deep blue-grey waterlogged subsoil and some highly oxidising tropical soils showed less difference for similar *p*H values than did pairs of soils from adjacent experimental plots with widely differing reactions.

In Fig. 2 a few illustrative data of E_h and *p*H are given. Each section has, for reference, the E_h-*p*H relation for the quinhydrone and Fig. 2 *a* also gives portions of the hydrogen and the oxygen electrode potential lines. It will be seen that most soils fall close to the quinhydrone line and all on the more highly oxidising side of it. There was no evidence that soils rich in manganese dioxide or ferric oxide gave especially high oxidation potentials, though they doubtless possessed great oxidising capacities. In every case high oxidation-reduction potentials of soils were associated with low pH values.

It is obvious that oxidation-reduction potentials measured under laboratory conditions must give only conventional values and that however useful these may be, they must differ from those under field conditions where the oxygen diffusion, water-level and the established microflora will affect the local oxidation-reduction level.

A waterlogged gley soil with characteristic iron mottling and dark stripes of manganese dioxide gave a moderately oxidising potential, even though it showed considerable amounts of ferrous iron when tested with acid and ferricyanide. The oxidation-reduction potential is thus no criterion of waterlogging and formation of ferrous compounds. It would appear that with the alternation of reducing and oxidising conditions the products are laid down independently. Thus ferrous iron may form insoluble vivianite and higher oxides of iron and manganese may be deposited as gels which age rapidly to insoluble and inert forms. Such independent precipitation might explain the characteristic mottling and banding of gley soils. Clearly in such soils there is no approach to reversible equilibrium between the reduced and oxidised materials analogous to the equilibrium between bases and acids in kationic exchange.

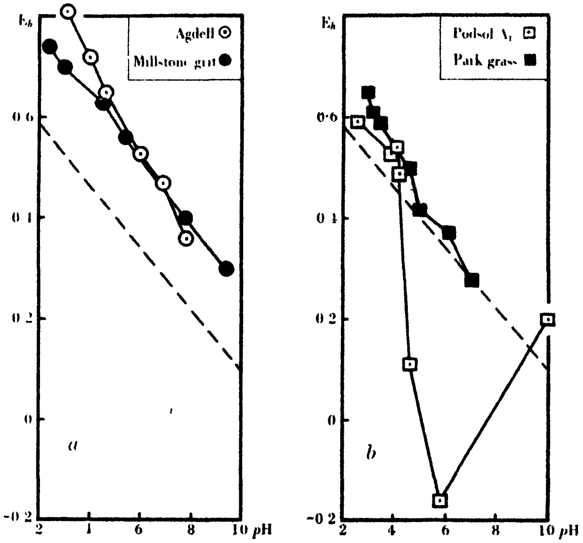


a *b* *c*

Fig. 2.

Measurements on plots of varied manurial treatment show no appreciable effect of manures, which is in accordance with Herzner's finding for a large number of Austrian arable soils, but contrary to some observations by Remesov (14) of marked effects on recently cultivated podsol soils rich in organic matter. This apparent contradiction will be discussed later. The changes in oxidation-reduction potentials with air drying are small for most soils. Appreciable differences were noticed only in soils with high contents of organic matter, the E_h becoming higher in some cases and lower in others, suggesting different forms of organic matter. Soils which have been air dried show no change in E_h over a long period.

Measurements of E_h changes when soils were treated with varying amounts of either HCl or $Ca(OH)_2$ gave results of the type illustrated in Fig. 3, where the E_h-*p*H curves for some typical soils, as well as the quinhydrone line, are given. The majority of soils gave curves on the more oxidising side of the quinhydrone line and more or less parallel to it. From the similarity between the curves obtained from soils treated with acid or base, and those from a wide range of soils at their natural *p*H values, with the quinhydrone line, it would appear that the system or systems governing the oxidation-reduction potentials were similar in nature to the quinhydrone system. Further, under normal conditions it seems likely that the factors responsible for the oxidation-reduction equilibrium are the reserves of oxidised and reduced materials rather than temporary occurrences of highly active materials.



a *b*

Fig. 3.

Willis (15) measured the oxidation-reduction potentials of an acid soil rich in organic matter after adding different amounts of lime. He concluded from the lower E_h values with the high additions of lime that in field liming the possibility of causing reducing conditions should be remembered. This conclusion is, of course, quite unjustified, for all of his measurements are on systems more oxidising than quinhydrone and his low E_h values after liming merely express high pH values. The error illustrates again the necessity for considering the pH values in all E_h measurements. An instance of the effect of liming claimed, but not demonstrated, by Willis was provided by the titration curve in Fig. 3 *b* for the humus horizon of a sandy podsol which for small additions of base developed a marked reduction potential (E_h 0·2 at pH 6). The explanation of this fall in potential is given in the following section.

E_h CHANGES OF SOIL SUSPENSIONS ON LONG STANDING.

The measurements already recorded were made on soil suspensions which had stood for a few hours. On further standing in closed vessels, opened only for the measurements, there were but small changes in the potentials for most soils within 24–48 hours. If the soils were waterlogged for a considerable period most soils gave slightly decreasing E_h values. The highly oxidising soils poor in organic matter had in general greater capacity than the less oxidising ones for maintaining their potentials.

A very marked fall in E_h after waterlogging for one or two days was observed with some Russian chernozem soils. In order to ascertain how far this effect was characteristic of the chernozem soil type, measurements were made on a series of soil samples collected by Drs Crowther and Richardson during the 1930 International Soil Congress. The samples represent the major soil types of European Russia from the podsol soils of the north through the grey forest soils to the chernozems and the chestnut soils. They are arranged in Table III in order from north to south and are thus in approximate order of decreasing acidity and increasing alkalinity. Their fertility passes through a maximum in the chernozems. The last sample is from a great height in the Caucasus Mountains.

The E_h values of the freshly prepared soil suspensions showed only small and irregular differences according to soil type or horizon, but on standing for one or two days there was a clear distinction between a group of soils which gave low E_h values and the others which showed but small changes on standing. All of the A and B horizon samples from chernozem soils showed a marked fall in E_h, which in some cases led even to negative values, which however were not closely reproducible. The mountain meadow soil behaved in a similar way and the chestnut soils showed slight falls in E_h. The other soils and all of the C horizons gave

Table III. E_h *and* pH *values of typical Russian soils.*

Place	Soil type	Vegetation	Horizon	Depth cm.	E_h after 2 hours	E_h after 24 hours	E_h after 48 hours	pH after 2 hours	pH after 24 hours	pH after 48 hours
Lisino (near Leningrad)	Strongly podsolised on varve clay without gley formation	Mixed forest	A 2	15–20	0·47	0·44	0·38	5·4	5·4	5·3
			B	40–45	0·46	0·44	0·36	6·6	6·4	6·4
			C	80–90	0·41	0·41	0·40	7·1	7·1	7·2
Starojilovo (Moscow District)	Dark grey forest soil	Cultivated for centuries after mixed forest	A 2	20–40	0·50	0·48	0·37	5·4	5·3	5·3
			B 1	60–65	0·54	0·55	0·55	5·4	5·3	5·3
			C 2	200–205	0·48	0·50	0·46	6·2	6·3	6·3
Starojilovo (Moscow District)	As above, in slight depression, highly degraded	As above	A 2	15–20	0·51	0·54	0·54	5·4	5·6	5·6
Khrenovaya (Central Chernozem District)	Crusty chernozem-solonetz influenced by ground water	Dense grass regularly cut for hay	A	0–10	0·48	0*	0·12	6·1	5·8	5·2
			B	10–20	0·49	0*	0·18	6·2	6·2	6·6
Voronesh	Chernozem (sample supplied by K. K. Gedroiz)	—	Surface	—	0·41	0*	0·25	6·0	6·0	6·0
					0·45	0*	0*	6·3	6·1	6·3
Izberdey	Deep chernozem	Cultivated	A 1	20–30	0·48	0*	0*	6·2	6·1	6·2
			B 1	65–75	0·47	0·25	0·25	6·4	6·4	6·9
			C	130–140	0·42	0·44	0·46	7·1	7·1	7·1
Kharkov	Deep chernozem (southern form)	Cultivated	B	40–50	0·41	0·35	0·32	6·8	7·7	7·7
			C	100–120	0·41	0·41	0·42	7·6	7·9	7·7
Verbluid (North Caucasus)	Azov chernozem	Recently ploughed from shrub steppe	A	0–20	0·44	0·37	0·33	8·0	7·0	7·0
Gashun	Deep columnar solonetz of chestnut zone in very slight depression	Virgin steppe, medium grass	A	0–8	0·45	0·37	0·31	6·9	6·7	6·7
			B 1	10–20	0·37	0·27	0·20	7·5	7·6	7·5
			C 1	50–60	0·40	0·45	0·43	7·5	7·8	7·8
Gashun	Chestnut	Virgin steppe, medium grass	A 1	0–12	0·35	0·18	0·34	7·3	7·3	7·2
			B 1	25–45	0·39	0·33	0·33	8·0	7·5	7·4
			C 1	65–95	0·42	0·40	0·40	8·0	8·1	7·9
Beketovka (near Stalingrad)	Chestnut soil slightly solonised	Virgin steppe	A 1	0–5	0·37	0·37	0·37	6·5	6·4	6·6
			A 2	15–25	0·42	0·38	0·36	6·8	6·4	6·6
			B 1	25–35	0·40	0·41	0·30	6·8	6·7	6·8
			C	70–80	0·41	0·44	0·38	8·2	7·6	7·8
Georgian Military Highway (highest point)	Grey mountain meadow soil (altitude 2100 m.)	Much coarse grass	A 1	5–12	0·48	0·33	0·10	5·1	5·6	5·6
			C	60–65	0·49	0·51	0·36	6·0	6·0	5·8

* The E_h values were poorly reproducible and varied irregularly from +0·2 to −0·2.

approximately constant values, with the exception of the C horizon of the mountain meadow soil, which yielded a considerable amount of ferrous iron after waterlogging. Even in chernozem soils, the fall of E_h can be completely inhibited by adding a trace of mercuric chloride or by treating the soil with dilute hydrogen peroxide. There can be no doubt that the fall in E_h is caused by microbiological activity in a system approaching anaerobic conditions.

Such falls in potential can be produced in any soil by addition of carbohydrates followed by waterlogging, but the form of the E_h-time curve for soils treated with glucose solution, in the manner originally studied by Gillespie, failed to give characteristic results for extreme kinds of soils. The E_h values reflect merely the intensity of the decomposition of carbohydrates by micro-organisms in the solution; the solid phase probably plays little part. Where, however, no carbohydrate is added to the soil, the E_h-time curves may be taken to show the presence or absence of readily oxidisable material in the original soil. Thus in the A and B horizons of the chernozem, in the mountain meadow, and in the humus horizon of a sandy podsol soil when limed in the laboratory, the marked fall in E_h indicates that readily oxidisable organic material is present. Most other soils, including an English fen soil, podsol soils and grey forest soils, do not contain such reserves of potential energy material.

In attempting to explain this grouping of soils it is convenient to consider first those soils which are sufficiently near neutrality to allow abundant bacterial activity when moisture and temperature conditions are suitable. The characteristic features of the chernozem belt of soils are low winter and high summer temperatures. The soil is moist for a short period in spring and early summer and under natural conditions a rapid growth of grass is followed by almost complete drying out. The plant roots and stubble decompose slowly on account of lack of moisture in autumn and of low temperature in winter. Organic matter accumulates, partly as material capable of being oxidised as soon as water supply and temperature allow, and partly as humus. In the laboratory experiments oxidation of the plant residues begins immediately, giving low E_h values comparable with those obtained when carbohydrates are added to other soils. In the drier chestnut soil region to the south of the chernozem belt the total plant growth is much less, and in the wetter north decomposition proceeds over much longer periods and little organic matter accumulates, except where some other condition, such as acidity, waterlogging, or low temperature, intervenes to restrict oxidation in the soil. It is noteworthy that chernozems which have been under cultivation for centuries also show by low E_h values that readily oxidisable organic material is present. The residues of cultivated crops naturally behave as those of the native flora under the extreme climatic conditions and remain unoxidised until the spring. Evidence that the total organic matter content is not responsible for the fall in E_h on waterlogging is given by English fen soils which behave as normal English mineral soils. Fen soils which were drained centuries ago are not now accumulating organic matter; on the other hand they are slowly losing under cultivation the vast reserves of humified material built up when they were swamps. Fresh plant residues must now be decomposed rapidly even under normal winter conditions.

Under conditions of extreme acidity, as in the humus layers of podsol soils, readily oxidisable organic matter may remain and accumulate. Fig. 3 *b* shows that on neutralising such a soil in the laboratory intense reduction may result from the anaerobic decomposition of this material. Remesov found similar results on podsol soils recently limed in the field. On the other hand, some acid humus horizons, as *e.g.* on certain plots of the Rothamsted Park Grass experiments, do not show intense reduction even after neutralisation, is as shown in Fig. 3 *b*. Presumably in such cases only very inert forms of organic matter are accumulating.

The conditions determining the production and decomposition of organic matter in the soil may thus be used to interpret the main changes in oxidation and reduction on waterlogging, but the potential measurements do not appear to add much to what may be deduced from the current theories of soil formation. All the E_h values presented here are measurements of oxidation-reduction intensities. The difficulty of measuring "poising" capacities in complex biological systems becomes still greater when a third phase, the solid, is introduced by the soil particles. It has not been possible to find a suitably "poised" system which would allow true equilibrium. Systems like ferro-ferricyanide proved to have complex reactions with the soil, and potential measurements in slightly oxidising solutions such as dilute hydrogen peroxide were complicated by changes in *p*H values.

SUMMARY.

1. The glass electrode with an electrometer triode valve as amplifier gives accurate *p*H measurements on soil suspensions and on soil crumbs moist enough to wet the glass. It has the advantages that it may be used in highly oxidising or reducing systems and in alkaline soil, but it

has little merit over the quinhydrone electrode where this is known to be reliable.

2. The glass electrode forms a satisfactory reference electrode in oxidation-reduction potential measurements, as it allows both E_h and pH measurements without alteration to the system, whilst its high resistance minimises polarisation.

3. Oxidation-reduction potentials of soils depend so closely on the pH value of the soils that they should not be considered separately. For constant pH values highly contrasted soil types may give similar oxidation-reduction potentials.

4. After waterlogging in the laboratory for one or two days, there is a marked fall in potential for soils known from the conditions of their formation to contain organic matter capable of rapid decomposition as soon as moisture, temperature and soil reaction become favourable. In the main soil zones of European Russia, this change on waterlogging reaches its maximum in the chernozem belt.

In conclusion the author wishes to acknowledge her indebtedness to Dr E. M. Crowther, Head of the Chemical Department, for his valuable help throughout the work and in the discussion of data.

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THE EFFECT OF IRRIGATION ON SOIL SALTS AT THE GEZIRA RESEARCH FARM, WAD MEDANI, SUDAN.

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(With Two Text-figures.)

INTRODUCTION.

THE abandonment of certain irrigation schemes has been ascribed (1, 2, 3) to the upward movement of subsoil salts into the root zone where they restrict or inhibit growth. To ascertain whether such movement occurred in the Gezira was one of the first tasks undertaken in this laboratory. The investigations described below extended from 1924 to 1931. They show that in the heavy and difficultly permeable soil of the Gezira Research Farm there is, under normal irrigation, practically no change in subsoil salts.

The salts seem to sink an inch or two when the soil is watered and to rise again when the soil dries out, but these changes have been traced not to a displacement of salts through the soil material but to swelling and shrinking of the less saline surface soil. Direct measurements of swelling were made by the late R. H. K. Peto in experiments described below, and in addition Messrs A. B. Miskin, J. H. O'Connor and C. E. Gibson of the Survey Department, Sudan Government, carried in 1928, 1929, 1930 and 1931 four series of levels across representative plots of the Gezira Research Farm. The resulting estimates of the upward and downward movement of the soil surface agree closely with the apparent fall and rise of subsoil salts. In view of this close agreement we have now discontinued the laborious sampling programme involved in the enquiry but may resume it after the lapse of some years in order to see whether any slight cumulative effect has escaped detection in the present series of observations. The results recorded here are probably applicable to the greater part of the eastern Gezira, but they may well have no bearing on the behaviour of lighter and more permeable soils elsewhere.

FIELD AND LABORATORY TECHNIQUE.

No progress was made with this investigation until the purchase of a satisfactory boring tool(4) enabled us to take large numbers of samples without disturbing the adjacent soil. In work specifically directed to the study of salt movement the procedure finally adopted was to sample fifteen plots at the end of each cotton season. During the period of this investigation the farm area was under a three-course rotation, either Egyptian cotton—sorghum—fallow, or Egyptian cotton—*Dolichos lablab*—fallow. Thus, of the fifteen plots, five had just been under cotton, five had borne a grain or leguminous crop, and five represented fallow land. In each plot ten or eleven 6 ft. bores were sunk at intervals of about 30 yards, care being taken that each hole was within a few yards of the corresponding hole sampled one year earlier.

Our normal practice is to take samples in twelve successive 6 in. steps. In April 1926 we tried taking samples in two 1 ft. steps, then eight 3 in. steps, and finally two 1 ft. steps in order to define more closely the upper limit of the subsoil salts which are usually encountered at a depth of 3 ft. This method proved unsatisfactory, and in April 1927 we reverted to sampling by successive 6 in. steps. These particulars refer to the end of season sampling which was directed to the study of salt movement under normal irrigation and involved the examination of some 12,000 samples. Additional information was obtained from the examination of some 50,000 samples collected during the course of other investigations, some of which represented abnormal conditions of soil and of irrigation practice.

Samples are collected in numbered bags and are allowed to become air dry. They are then pounded by hand and 20 gm. lots are weighed into wide-mouthed bottles to which water (100 c.c.) is added. The bottles are shaken by hand for a few seconds and are allowed to stand overnight in felt-lined boxes. Some 18 hours after addition of the water the bottles are vigorously shaken for about half a minute and the electrical resistance of the turbid suspension is then determined. The percentage (X) of salt in the sample is then calculated from the equation

$$X = \frac{250}{\text{Spec. Res. at } 30^\circ}.$$

Under Sudanese conditions the suspensions vary in temperature from 20 to 35° C., and a correction of 2 per cent. per 1° C. is applied to the readings to give specific resistance at 30° C. Joseph(5) has noted that informative results are obtained by this means in spite of the fact that equal conductances are not necessarily the result of equal weight concentrations. In this paper Joseph gives particulars as to the chemical and mechanical composition of various soils in the canalised area, and his figures may be taken as covering the samples examined in the present enquiry. A detailed description of the soil profile at the Gezira Research Farm (6) may also be consulted, but it is sufficient to note here that variations in salt content as determined by conductimetric measurements are closely associated with the presence or absence of gypsum which occurs in fairly well-defined horizons.

One point of interest in this connection is that at the end of 18 hours the process of extraction is not equally advanced in surface samples which yield mainly sodium bicarbonate and in subsoil samples which yield mainly sodium sulphate and usually contain an undetermined amount of the sparingly soluble gypsum. Table I gives results of conductimetric measurements made at intervals during the long-continued extraction of a typical set of samples. It will be seen that for gypsum-free samples the 18-hour figures approximate to the zero time values and for gypsum-bearing samples to their equilibrium values.

Table I.

		Gypsum absent	Gypsum present	Gypsum present
Soil zone under examination		0–36 in.	36–54 in.	54–72 in.
Per cent. salts:	7 min.	0·094	0·274	0·483
	18 hours	0·104	0·554	0·899
	345 days	0·252	0·674	1·127
	763 days	0·299	0·719	1·187
	1115 days	0·335	0·719	1·203

In these soils the process of extraction differs widely from the simple separation of soluble salts from an inert residue. In routine salt examinations, whether conductimetric, gravimetric or other, some arbitrary decision must be made as to the conditions of the extraction and this necessarily affects the interpretation of the results. The depths at which there are changes in the soil column can be ascertained with precision, but the actual estimates of salt content require care for their correct interpretation. Table II gives results obtained from eleven 6 ft. bores sunk in plot 75 in April 1929. It will be noticed that in each bore the salt content rises sharply to a maximum, falls slightly and then rises again. The maximum and minimum are clearly shown in the average in the right-hand column of the table. In other cases it sometimes happens that the maxima of some bores lie at the same depth as the minima of other bores, and average figures may then fail to show this

Table II. *Illustrating method of condensing results. Plot* 75, *April* 1929.

Step	Depth in.	Bore No.											Average
		2	4	6	8	10	12	14	16	18	20	22	
1	3	0·130	0·094	0·153	0·088	0·108	0·134	0·086	0·175	0·106	0·106	0·126	0·119
2	9	0·134	0·092	0·148	0·115	0·100	0·155	0·087	0·091	0·112	0·126	0·094	0·114
3	15	0·10	0·10	0·13	0·10	0·09	0·12	0·08	0·12	0·10	0·11	0·11	0·11
4	21	0·09	0·10	0·11	0·14	0·11	0·13	0·09	0·15	0·11	0·12	0·11	0·11
5	27	0·15	0·11	0·15	0·13	0·13	0·15	0·09	0·13	0·11	0·12	0·12	0·13
6	33	0·19	0·25	0·14	0·59	0·17	0·15	0·11	0·19	0·13	0·19	0·17	0·21
7	39	0·37	0·63	0·19	0·68	0·33	0·15	0·19	0·61	0·52	0·50	0·57	0·43
8	45	0·52	0·61	0·34	0·68	0·56	0·65	0·62	0·64	0·52	0·62	0·55	0·57
9	51	0·57	0·45	0·42	0·64	0·50	0·56	0·50	0·57	0·52	0·42	0·58	0·52
10	57	0·42	0·47	0·34	0·47	0·32	0·41	0·54	0·40	0·29	0·33	0·49	0·41
11	63	0·61	0·78	0·37	0·38	0·31	0·31	0·67	0·29	0·40	0·62	0·64	0·49
12	69	0·70	0·90	0·61	0·43	0·59	0·59	0·72	0·55	0·64	0·68	0·73	0·65
Average to 6 ft.		0·33	0·38	0·26	0·37	0·28	0·29	0·32	0·33	0·30	0·33	0·36	0·32
Salt content of top foot		0·132	0·093	0·150	0·101	0·104	0·145	0·087	0·133	0·109	0·116	0·110	0·117
a. Depth of soil of salt content less than 0·2 %		33	27	39	27	33	39	39	33	33	33	33	34
A. Amount of salt at this depth		0·19	0·11	0·19	0·13	0·17	0·15	0·19	0·19	0·13	0·19	0·17	0·165
b. Depth of maximum		51	39	51	42	45	45	45	45	45	45	39	45
B. Amount of salt at maximum		0·57	0·63	0·42	0·68	0·56	0·65	0·62	0·64	0·52	0·62	0·57	0·59
c. Depth of minimum		57	51	57	63	63	63	51	63	57	57	45	57
C. Amount of salt at minimum		0·42	0·45	0·34	0·38	0·31	0·31	0·50	0·29	0·29	0·33	0·55	0·38
Salt content of sixth foot		0·65	0·84	0·49	0·40	0·45	0·45	0·70	0·42	0·52	0·66	0·69	0·57

characteristic fluctuation in salt content. For this reason it has seemed advisable to note for each bore the particulars shown at the foot of the table and to take the average of these as representing the plot under examination.

In this method of condensing the results attention is focused on the depths *a*, *b*, *c* at which certain features of the soil profile are encountered. The depth *a* of soil of salt content less than 0·2 per cent. presumably represents the eluvial zone. Whether *b* can be taken as a centre of an illuvial zone and *c* as the existing limit of weathering processes is not quite clear. This view has the merit of simplicity and has been advocated by Vageler(7) on the basis of observations published from this country. It should, however, be noted that in these heavy clay soils a considerable part may be played by processes other than those customarily associated with Glinka's system of designating horizons in the soil profile.

At the moment it is sufficient to regard the depths *a*, *b* and *c* as specifying certain features of the profile without taking up a definite stand as to their genetical significance. Attention must now be drawn to one source of error in this method of presenting the data. The results shown in Table III were obtained for a plot (not in the Gezira Research Farm) which was sampled before and after a season's irrigation.

Table III. *Plot Dolga* 2 *C. Percentage salts.*

Step	Depth in.	Before irrigation	After irrigation
1	3	0·08	0·08
2	9	0·09	0·10
3	15	0·11	0·12
4	21	0·31	0·15
5	27	0·66 max.	0·44
6	33	0·55 min.	0·59
7	39	0·66	0·70
8	45	0·82	0·79
9	51	0·80	0·81 max
10	57	0·79	0·75 min.
11	63	0·74	0·77
12	69	0·60	0·72

In this case the comparison of depths in respect to salt maximum and minimum is evidently fallacious. A real translocation of salt from step 5 to step 6 may have occurred, but it is more likely that the method of sampling by 6 in. steps did not adequately show up the distribution of salts in the samples taken after irrigation. The same difficulty is met in some of the results under review in this report, but since the number of observations is large it was thought that errors of this kind would occur with sufficient regularity to make the comparison legitimate. It will in fact be found that apparent displacements of the upper salt zone (that is variations in the depth *a*) tally fairly well with apparent displacements of lower zones (that is variations in the depths *b* and *c*).

The dependence of the depth figures *a*, *b* and *c* upon the size of the sample unit is shown by the fact that it has been found necessary to discard results obtained in April 1926, when, as stated above, a mistaken attempt was made to concentrate on the third and fourth foot instead of sampling by uniform 6 in. steps. It may be added that results subsequently obtained have been inspected in order to see whether the method now employed has given seriously misleading figures for depth as in the example quoted above. In no case was it necessary to alter the average figures representing a group of plots sampled by fifty or sixty borings. The use to which the data have been put is sufficiently illustrated by Table IV, which affords a comparison of seven plots sampled in April 1927 after a season's fallow and again in April 1928, that is at the end of the subsequent cotton season.

RESULTS OF END OF SEASON SAMPLINGS.

(1) *Cotton after fallow.*

The average results given in Table V are derived, as shown in Table IV, by comparing data for a group of plots which in April of one year had lain fallow and in April of the next year had grown cotton. As explained above the comparison is invalid for the sampling of 1926 and 1927, but the five samplings from 1927 onwards provide four comparisons giving a fair measure of the apparent changes.

Table V clearly shows that the apparent salt content of the top foot of the soil is appreciably increased by a season's irrigation. This change appears to be due to simple moistening of the soil and not to the introduction of soluble salts present in irrigation water. A similar change has been observed in laboratory experiments in which soil was moistened and was also noted as a consequence of rain. Thus the effect of the rains of 1928 was shown by samples taken from five fallow plots for which the following are average results: April 1928, first foot salts 0·078 per cent.; October 1928, 0·097 per cent.; April 1929, 0·075 per cent. In the laboratory, water, in quantities ranging from 0 to 14 c.c., was added to 20 gm. lots of air-dry surface soil contained in loosely stoppered bottles which were examined 1, 6 and 14 weeks after addition of the water. The results (apparent salt content per cent. on soil) are shown in Table VI. It appears from this that the immediate effect of moistening

Table IV. *Data for seven plots, fallow in April* 1927 *and at end of subsequent cotton season April* 1928.

Plot	First foot salts		*a*		*b*		*c*		*A*		*B*		*C*		Sixth foot salts		Average salts 0–6 ft.	
	1927	1928	1927	1928	1927	1928	1927	1928	1927	1928	1927	1928	1927	1928	1927	1928	1927	1928
16	0·096	0·097	33	31	49	44	60	59	0·13	0·15	0·66	0·67	0·55	0·47	0·62	0·57	0·32	0·35
18	0·087	0·096	32	34	47	46	58	59	0·15	0·15	0·64	0·65	0·51	0·37	0 70	0·67	0·37	0·33
20	0·078	0·082	31	32	43	43	58	58	0·13	0·13	0·58	0·57	0·35	0·37	0·54	0·55	0·31	0·31
23	0·086	0·106	32	33	49	48	58	58	0·12	0·14	0·59	0·62	0·52	0·52	0 65	0·72	0·32	0·35
24	0·062	0·102	38	38	57	57	61	62	0·13	0·13	0·61	0·53	0·56	0·50	0·69	0·63	0·28	0·27
25	0·080	0·107	32	35	51	56	58	63	0·13	0·14	0·65	0·63	0·58	0·59	0·75	0·69	0·37	0·32
29	0·062	0·128	33	33	44	49	50	56	0·13	0·16	0·47	0·66	0·38	0·56	0·61	0·79	(0·39)	0·39
Average	0·079	0·103	33	34	49	49	58	59	0·13	0·14	0·60	0·62	0·51	0·49	0·65	0·66	(0·33)	0·33

Table V. *Summary of data for plots sampled before and after a cotton season.*

		First foot salts		*a*		*b*		*c*		*A*		*B*		*C*		Sixth foot salts		Average salts 0–6 ft.	
1926	1927	0·081	0·093	28	32	—	—	—	—	0·15	0·13	—	—	—	—	—	—	0·31	0·32
1927	1928	0·079	0·103	33	34	49	49	58	59	0·13	0·14	0·60	0·62	0·51	0·49	0·65	0·66	(0·33)	0·33
1928	1929	0·076	0·122	31	33	45	46	55	58	0·13	0·15	0·58	0·59	0·42	0·41	0·63	0·60	0·33	0·33
1929	1930	0·075	0·097	32	33	44	45	55	57	0·15	0·15	0·54	0·62	0·40	0·46	0·60	0·64	0·32	0·34
1930	1931	0·082	0·091	29	34	44	49	54	59	0·15	0·15	0·62	0·61	0·48	0·46	0·68	0·61	0·37	0·32
Average		0·079	0·101	30·6	33·2	45·5	47·2	55·5	58·2	0·142	0·145	0·58	0·61	0·45	0·45	0·64	0·63	0·33	0·33

soil is a reduction in apparent salt content, and that this process is reversed within a period which depends on the moisture content of the soil. The mechanism of the initial reduction is not understood; the secondary increase seems analogous to the slow extraction of electrolyte illustrated in Table I above. In the field rain and irrigation promote nitrification as well as inducing an increase in apparent salt content. The two processes are not necessarily associated however, for in the laboratory test quoted in Table VI nitrification was suppressed(8) in soil containing 70–80 per cent. moisture, whereas the secondary increase in apparent salt content was comparatively rapid.

Table VI.

	Moisture content (% on dry soil)				
	5	16	26	48	68
Salt content after 1 week	0·08	0·06	0·06	0·07	0·08
„ 6 weeks	0·09	0·06	0·08	0·10	0·11
„ 14 „	0·08	0·06	0·09	0·12	0·13

We now turn to the apparent depression of subsoil salts: 2·6, 1·7 and 2·7 in. for depths *a*, *b* and *c* giving a mean depression of 2·3 in. This change may be ascribed in the main to swelling of the surface soil in consequence of its increased moisture content, but one should note that the surface of fallow soil was ridged in preparation for cotton and did not provide a good datum level for sampling. Our practice has been to drop a heavy rail on the ground and to measure depths from the lower surface of the rail. At the end of a cotton season the ridges are pretty well flattened out and there is less difficulty in finding a datum level. The comparison of depths *a*, *b* and *c* before and after a cotton season is obscured to some degree by this uncertainty as to precisely where the soil surface lies, and the figures for apparent depression of subsoil salts are therefore best taken to the nearest inch, that is 2 in. instead of 2·3 in.

It will be seen that there is practically no change in the amounts of salt *A*, *B* and *C*. Averages for salt content of the sixth foot are included merely to facilitate the preparation of Fig. 1, which is a conventional representation of salt distribution. The average salt content for the top 6 ft. of soil is little more than an arithmetical check which enables one to see whether or not a plot has been fairly sampled. In this case (cotton after fallow) there is no change in the average salt content for the top 6 ft., whereas a slight reduction would be expected in view of the fact that since the surface soil has swelled a 6 ft. column includes a smaller proportion of the saline subsoil. The expected reduction is offset by the increase in apparent salt content of the surface soil and by the introduction of salts contained in the irrigation water.

(2) *Grain (sorghum) or leguminous* (Dolichos lablab) *crop after cotton.*

At the end of a cotton season the soil lies bare for the months of May and June and then receives the rains of July and August. Sorghum and *Dolichos lablab* are sown about the end of July and now receive two or three waterings up to the end of October. During the period of this investigation the leguminous crop was watered up to the end of December. After these crops are harvested the soil lies bare until the following rains. When sampled in April the surface of the bare soil is fairly flat, so that the difficulty as to datum level does not arise. The total amounts of irrigation received by the different crops are somewhat as follows: Egyptian cotton 6400 $m.^3$ per acre, sorghum 1250 $m.^3$ per acre, *Dolichos lablab* 2500 $m.^3$ per acre on the former system and 1250 $m.^3$ per acre on the present system.

In a year of heavy September rain these waterings are considerably reduced.

Table VII was prepared in the same way as Table V and provides four comparisons of land at the end of a cotton season with the same land one year later, that is after a grain or leguminous crop. No attempt has been made to separate these two crops in respect to their effect on soil salts.

Table VII shows a decrease in the apparent salt content of the top foot of soil. It appears therefore that as the soil dries out it returns fairly rapidly to its initial state in respect to the readiness with which electrolytes pass into solution in our routine process of extraction. Other investigations, not yet published in detail, have shown that watering induces a change in the physical state of Gezira soil and that this change is reversed by fallowing. The presumption is therefore that the change in apparent salt content of the top foot is largely dependent on the change in its physical state.

In respect to the depth figures, *a*, *b* and *c* the comparisons show that these are reduced as the soil dries out, *i.e.* the subsoil salts lie nearer to the soil surface. The figures are less consistent than those of Table V, the average reduction being 1·5 in. This change is due in the main to shrinking in the surface layers.

No significance is attached to the small changes in salt contents *A*, *B* and *C*. The small increase in average salt content of the 6 ft. column

Table VII. *Summary of data for plots sampled at end of a cotton season and again one year later after a grain or leguminous crop.*

		First foot salts		*a*		*b*		*c*		*A*		*B*		*C*		Sixth foot salts		Average salts 0–6 ft.	
1926	1927	0·081	0·078	32	28	—	—	—	—	0·14	0·13	—	—	—	—	—	—	—	—
1927	1928	0·093	0·076	32	31	46	45	57	57	0·13	0·15	0·57	0·61	0·45	0·45	0·63	0·62	0·32	0·34
1928	1929	0·104	0·086	34	31	49	50	59	57	0·14	0·14	0·61	0·62	0·50	0·49	0·66	0·62	0·33	0·34
1929	1930	0·119	0·082	33	31	46	45	59	57	0·15	0·15	0·59	0·61	0·41	0·40	0·59	0·64	0·33	0·33
1930	1931	0·097	0·080	33	30	45	44	57	55	0·15	0·14	0·62	0·62	0·46	0·44	0·64	0·62	0·34	0·35
Average		0·099	0·080	32·8	30·2	46·5	46·0	58·0	56·5	0·144	0·142	0·60	0·62	0·46	0·45	0·63	0·63	0·33	0·34

Table VIII. *Summary of data for plots sampled after a grain or leguminous crop and again one year later after bare fallow.*

		First foot salts		*a*		*b*		*c*		*A*		*B*		*C*		Sixth foot salts		Average salts 0–6 ft.	
1926	1927	0·078	0·081	30	33	—	—	—	—	0·14	0·13	—	—	—	—	—	—	—	—
1927	1928	0·078	0·076	28	31	44	45	53	55	0·13	0·13	0·62	0·59	0·46	0·43	0·65	0·64	0·37	0·34
1928	1929	0·079	0·075	31	32	44	44	55	55	0·15	0·15	0·61	0·56	0·44	0·40	0·63	0·60	0·34	0·31
1929	1930	0·084	0·078	31	30	47	44	56	54	0·14	0·15	0·62	0·59	0·50	0·48	0·64	0·68	0·34	0·36
1930	1931	0·082	0·073	31	30	45	44	57	55	0·15	0·13	0·61	0·61	0·40	0·43	0·64	0·63	0·33	0·37
Average		0·080	0·077	30·2	31·2	45·0	44·2	55·7	54·7	0·142	0·138	0·61	0·59	0·45	0·43	0·64	0·64	0·35	0·35

may, however, be ascribed to the fact that this includes, in the case of the bare soil, a larger proportion of saline subsoil.

(3) *Fallow after grain or leguminous crops.*

The comparison presented in Table VIII is between land which has borne a grain or leguminous crop and has then lain bare till April with the same land one year later, when the summer rains have intervened and after some months of bare fallow the soil has been prepared for the ensuing cotton crop.

It is sufficient to note that the figures show a further small reduction in the apparent salt content of the top foot and a slight reduction in depth figures *a*, *b* and *c*.

In order to obtain an idea as to the effect of a complete rotation it is now possible to combine the average results of Tables V, VII and VIII.

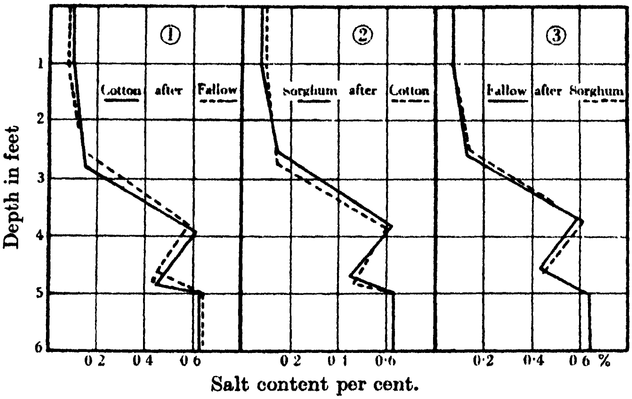

Fig. 1. Conventional representation of salt distribution as affected by crop rotation.

There is no net change in the apparent salt content of the top foot, there is a rather questionable indication that the subsoil salts have been washed downwards through the soil for about half an inch, and there is a slight increase in the average salt content of a 6 ft. column. This slight increase represents 1·8 tons of electrolyte per acre, whereas the amount of soluble salt introduced by the irrigation water during a three-year period is about 1 ton per acre. The difference is within the limits of experimental error.

Fig. 1 is a conventional representation of the apparent changes discussed in this section. For convenience the readings have been abbreviated to "sorghum after cotton," etc., although, as stated above, both sorghum and *Dolichos lablab* were grown. The continuous lines show later phases and the dotted lines earlier phases of the rotation, so that in cotton after fallow the figure shows an apparent depression of salts and in sorghum after cotton an apparent rise of salts.

PETO'S WORK ON SOIL MOVEMENT.

As published observations (9, 10) on this subject are not readily accessible a brief note may usefully be included here.

In one experiment bore holes about 2 in. in diameter were sunk to depths of 1, 2, 3, 4, 5, 6 and 7 ft. in a small plot. Plates carrying a tell-tale rod protected by a guard tube were lowered into the bores and soil was rammed back over them by means of a stout iron pipe. The projecting ends of the tell-tale rods thus served to show the position of the plates in relation to the deepest plate which lay beyond the expected depth of water penetration. The plot was flooded for three weeks and a few days later the heights of the tell-tale rods were accurately measured by use of a level. Upward movements of the plates in relation to the 7 ft. plate were as follows:

Soil surface	1 ft. plate	2 ft. plate	3 ft. plate	4 ft. plate	5 ft. plate	6 ft. plate	7 ft. plate
5·0 in.	2·9 in.	1·5 in.	0·7 in.	0·4 in.	0·1 in.	0·0 in.	Datum

The method of sinking indicator rods was subsequently applied to four squares used for comparing different ways of applying gypsum. In this case the squares were flooded for one week instead of three as in the previous experiment. Table IX gives the rise in inches of the soil surface and of plates sunk at depths of 1, 2, 3, 4 and 5 ft.

Table IX.

	Surface	1 ft.	2 ft.	3 ft.	4 ft.	5 ft.
1. Fine gypsum	3·9	2·3	1·5	0·7	0·2	0·0
2. Coarse gypsum	3·6	2·0	1·6	1·0	0·0	0·0
3. Plaster of Paris	3·7	2·5	1·8	0·9	0·3	0·0
Mean	3·7	2·3	1·6	0·9	0·2	0·0
No gypsum	3·1	1·6	1·2	0·4	0·0	0·0

These observations provide an elegant check on the estimates of water penetration which were based on soil moisture content determined before and after flooding. These estimates were as follows: no gypsum 42 in.; coarse gypsum 57 in.; finely ground gypsum 57 in.; plaster of Paris 63 in. These materials were applied in chemically equivalent amounts and at the rate of 2 tons gypsum per acre.

It may be added that this demonstration of soil swelling in the field implies changes in the apparent specific gravity of the surface layers. The dry weight (tons per acre) of material contained in the top 6 in. of soil was accordingly determined and was found to be related to moisture content per cent. of dry soil as follows:

Moisture %	Dry weight
47	656
33	706
14	810

The direction and extent of these variations agree well with the foregoing observations on soil swelling.

The next stage in the enquiry was to obtain the assistance of officers of the Survey Department in taking levels across representative plots so as to ascertain the extent of soil movement under normal cultivation and irrigation. Messrs Miskin, O'Connor, and Gibson accordingly carried, by kind permission of Lt.-Col. S. L. Milligan, C.M.G., D.S.O., Director of Surveys, four series of levels in successive years across three strips of land, running from east to west across the farm and including the plots sampled by us. Each strip was about 1200 m. long and 280 m. wide, enclosing an area of about 75 acres. The strip area covered fifteen farm plots, and levels were taken at six points (*a*, *b*, *c*, etc.) in each plot.

Table X. *Plots* 62–76 (*southern strip*).

	Line ...	*a*	*b*	*c*	*d*	*e*	*f*
1928	Fallow	400	440	406	390	396	363
1929	Cotton	452	455	429	414	413	388
1930	Sorghum, etc.	387	399	370	347	342	329
1931	Fallow	375	382	369	364	351	317

Table XI. *Plots* 16–30 (*middle strip—about* 300 *m. north of plots* 62–76).

	Line ...	*a*	*b*	*c*	*d*	*e*	*f*
1928	Cotton	351	364	337	331	338	301
1929	Sorghum, etc.	287	303	280	258	279	253
1930	Fallow	303	307	292	289	271	282
1931	Cotton	365	381	363	346	362	342

Table XII. *Plots* 31–45 (*northern strip—just north of plots* 16–30).

	Line ...	*a*	*b*	*c*	*d*	*e*	*f*
1928	Sorghum, etc.	236	236	243	229	242	221
1929	Fallow	238	243	231	227	246	219
1930	Cotton	303	283	273	278	270	267
1931	Sorghum, etc.	264	278	252	240	254	233

The points *a*, *b* and *c* fell in the south half of each plot, whilst *d*, *e* and *f* fell in the north half. In Tables X–XII are given the average values (for the fifteen plots in each strip) for each of the six points (mm. above an arbitrary datum).

The observations summarised in Tables X, XI and XII are presented in Fig. 2 which gives an average cross-section of the farm from south to north. The diagram was constructed by taking lines *a*, *b* and *c* as representing the south half of the strip and lines *d*, *e* and *f* as representing the north half. (The points at which levels were staggered giving two triangles in each plot. As the ground slopes from south-east to north-west it is inconvenient to plot the simple averages given in Tables X, XI and XII.) It is evident from the figure that levels are higher after cotton than after sorghum or fallow. The changes in level work out as follows:

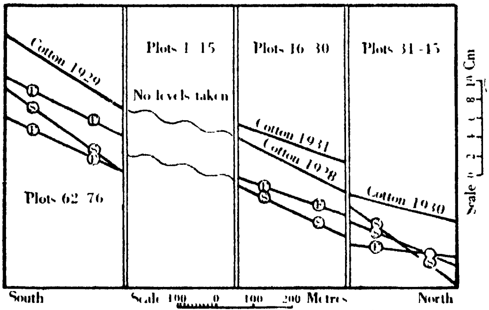

Fig. 2. Average cross-section of the Gezira Research Farm from south to north showing dependence of surface level on cropping. A three-course rotation is used: Cotton—sorghum or *Dolichos lablab* (*S*)—Fallow (*F*).

Cotton after fallow: 37, 56 and 46 mm.; mean rise of surface 46 mm. or 1·8 in.

Sorghum after cotton: 62, 49 and 39 mm.; mean fall of surface 50 mm. or 2·0 in.

Fallow after sorghum: 15 mm. fall, 15 mm. rise, 10 mm. rise; mean rise of surface 3 mm. or 0·1 in.

These results are in close agreement with the apparent changes in depth of subsoil salts. For cotton after fallow we have 1·8 in. rise of soil surface and 2·3 in. for apparent depression of subsoil salts. For sorghum or *Dolichos* after cotton the soil surface falls to 2·0 in., whereas the subsoil salts are found to be 1·5 in. nearer the surface. For fallow after grain or leguminous crop the survey results show 0·1 in. rise of soil surface, whereas the mean apparent change in subsoil salts (Table VIII) is that these lie 0·3 in. nearer the surface. Thus the two sets of observations agree to half an inch provided that under normal irrigation penetration of water and therefore soil swelling is limited to the top 30 in. of soil. For the land under consideration this is the case (cf. Greene (11)), and the conclusion may therefore be drawn that apparent changes in the depth of subsoil salts are largely accounted for by swelling or mechanical loosening and shrinking or compacting of the overlying soil. Apart from this there may be a real downward movement of salt at the rate of 0·5 in. in three years. Although the extent and direction of this real movement require confirmation by further studies undertaken after the lapse of some years, the present observations show quite definitely that in these soils there is under normal irrigation no appreciable upward movement of subsoil salts.

SUBSIDIARY OBSERVATIONS ON SALT MOVEMENT.

It is not proposed to present here more than a very brief account of the extensive data which have accumulated during the course of various investigations.

(1) It was found that watering promotes rapid changes in soil salts when their normal distribution has been inverted. A pit was excavated in successive layers to a depth of 6 ft. and the soil was then replaced foot by foot in inverse order. Subsequent observations were as follows:

Table XIII.

Date	Treatment	1st ft.	2nd ft.	3rd ft.	4th ft.
Feb. 1925	Before excavating	0·10	0·09	0·38	0·59
Feb. 1925	After inversion	0·55	0·46	0·59	0·38
Apr. 1925	After 3 waterings	0·50	0·62	0·65	0·38
Oct. 1925	,, 3 ,, and rain	0·42	0·57	0·40	0·40
Apr. 1926	,, 14 ,, ,,	0·12	0·37	0·40	0·40
Sept. 1926	,, 15 ,, 2 rains	0·12	0·41	0·44	0·43
May 1927	,, 26 ,, 2 ,,	0·10	0·25	0·33	0·44
Nov. 1927	,, 26 ,, 3 ,,	0·07	0·20	0·21	0·29
May 1928	,, 34 ,, 3 ,,	0·07	0·11	0·26	0·33
Nov. 1928	,, 36 ,, 4 ,,	0·09	0·07	0·13	0·17

These figures show that with successive waterings and rain the disturbed soil returned fairly rapidly to a salt distribution resembling that of a normal Gezira soil.

(2) Further definite evidence of salt movement has been obtained from experiments in which gypsum applied to the soil surface has reacted with the soil, producing in the top foot or 18 in. sodium sulphate in amount roughly equivalent to the dressing applied. It was not possible

to demonstrate exact equivalence, since, as noted above, simple watering produces a change in the apparent salt content of surface soil and our observations are not sufficiently precise to enable us to make accurate allowance for this factor. When waterings are applied to soil treated in this way sodium sulphate is washed from the surface layers and presumably reacts with the subsoil, increasing its content of sodium and producing other sulphates, for the most part gypsum. As gypsum is already present in the subsoil this secondary change is not accompanied by an increase in the apparent salt content of the subsoil, although estimations of total sulphate will doubtless show an increase at a depth of 2 or 3 ft.

(3) The obliteration of the maximum and minimum illustrated in Table III is rare, and when it occurs subsequent samplings show a return to the normal salt profile as the soil column dries out.

(4) Apparent depression of the salt zone is a regular consequence of watering and is followed by an apparent rise as the soil dries out. The foregoing observations make it clear that these apparent changes are largely due to movements of the soil surface.

(5) In a number of experiments the lower zone of salts seems to have remained stationary in relation to the soil surface. As these observations have not been analysed with the care given to the end of season samplings it seems likely that they are due to chance.

(6) The dependence of these changes on watering is shown (1) by absence of change in unirrigated land, (2) by absence of change in land which takes up very little water either owing to high demand of the crop (*i.e. Medicago sativa*) or owing to natural impermeability of the soil.

SUMMARY.

In order to ascertain whether subsoil salts moved upwards under the influence of irrigation an elaborate investigation was carried out at the Gezira Research Farm, Medani. It was found that the small apparent changes which occur under normal irrigation and cultivation are largely due to swelling and shrinking of the surface soil occasioned by changes in moisture content and to mechanical disturbance and settling which depend on cultivation. Apart from these apparent changes there may be a small downward movement of salt through the soil material; there is no upward movement.

When the salt content of the surface soil is increased by application of soil improvers or by other means, rains and watering rapidly wash

down the salt and in the course of time the soil column returns to its normal profile.

Salts introduced by the irrigation water are also washed down from the surface layers. The observations recorded show an increase in the average salt content of a 6 ft. column of soil which is roughly equivalent to the amount of salt introduced (about 1 ton per acre per 3 years).

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STUDIES IN TROPICAL SOILS.

III. THE SHRINKAGE BEHAVIOUR OF LATERITIC AND KAOLINITIC SOILS.

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I. INTRODUCTORY.

IN an earlier paper (1), the writer drew attention to the fact that certain tropical red soils exhibit relatively low shrinkage when moist blocks at the "sticky point" are dried in air. This peculiarity was attributed to a low proportionate amount of "vesicular water" as compared with the total amount of water absorbed or imbibed by the colloidal component of the soils, so that the red soils may be supposed to possess low "vesicular coefficients" (2), owing perhaps to the peculiar micro-structure of their colloidal matter.

The method employed by the writer for measuring shrinkage coefficient involves serious errors due to warping, but Haines (3) has demonstrated that this difficulty may be overcome by a procedure which accurately determines volume shrinkage directly. Haines' method depends on the periodic measurement of the volume of a drying soil block by displacement of mercury in a specially constructed specific gravity bottle. His results are plotted as volume of water content relative to the apparent volume of the soil block. The graphs appear to consist of two distinct straight line portions, the one representing "normal shrinkage" (in which the diminution in volume is exactly equal to the volume of water lost), the other representing "residual shrinkage" (in which the volume loss is much less than the volume of water evaporated, so that air gains access to the block). Among the materials whose shrinkage values were determined by Haines, *kaolin* exhibited no residual shrinkage whatever, differing essentially in this respect from certain other clays.

Haines considered that *residual* shrinkage is due solely to the presence of colloidal matter (probably occurring as coatings around the mineral soil grains), and that its magnitude furnishes a measure of colloidal content. He attributed *normal* shrinkage to loss of interstitial water, although he suggested that the *total* shrinkage depends, at least qualitatively, on clay content. Fisher (4) drew attention to this discrepancy, and referred to his earlier work on the evaporation of water from soil (5) in order to show that "normal shrinkage is due to the loss of both imbititional (*i.e.* 'colloid') *and* interstitial water when these are present together," since "imbibitional water evaporates with great ease, and comes off *before* the last several per cent. of interstitial or capillary water." Fisher's experimental technique has been criticised, however, by Keen, Crowther and Coutts (6), but their own results show that a constant rate of evaporation is maintained down to low moisture contents, both by sand and by soil alike.

It appears to the writer that the demonstrable facts of soil shrinkage and of water evaporation from moist soil may perhaps satisfactorily be explained by assuming a reticulate micro-structure for soil colloidal matter as postulated by Wilsdon (2) and previously discussed by the writer (1). This explanation will be attempted in a following section.

II. EXPERIMENTAL.

In order to study the shrinkage behaviour of tropical red soils, and to compare it with that of other soil types and of kaolin, the writer has redetermined by Haines' method the shrinkage values of the red soils described in the earlier paper, and has extended the investigation to include other red soils ,and numerous examples of kaolins (including pipe-clays derived by weathering from acidic igneous rocks), and of clay types generally classed as "grey soils."

In each case, the material was first sifted through a 100-mesh to the linear inch sieve, and then twice washed with excess of $N/2$ acetic acid, followed by several washings with tap water, and finally with distilled water until the washings were neutral to litmus. This treatment should remove most of the exchangeable bases that might appreciably affect some of the physical attributes of the soils.

The results obtained are presented in Table II, and the origin and relationships of the materials investigated are noted in Table I. The soils are grouped into (A) red soils, derived by weathering from basic and intermediate igneous rocks; (B) red soils, derived from limestone; (C) kaolinitic materials, derived mainly from acidic igneous rocks; and (D) other materials, mainly grey and yellow clay soils. Most of the samples examined occur in the West Indies. For comparison, some of Haines' results (E) are also included in Table II. Within each group, the materials are arranged in order of decreasing sticky-point moisture

Table I. *Notes on samples.*

(A) *Red soils derived from basic and intermediate igneous rocks.*

1.	Dominica.	Mt Joy Estate. Hypersthene andesite lava.
2.	Java.	Pasar Minggoe, Batavia. Trachytic tuff (?).
3.	Grenada.	Windward Coast cacao estates. Augite andesite lava.
4.	British Guiana I.	Tiger Hill. Hornblende schist.
5.	British Guiana II.	Hope Quarry. Demerara River. Dolerite dyke.
6.	Hawaii.	Koolan, Oahu. Basalt lava and ash.
7.	Cuba (Nipe).	Guara Estate, Oriente. Serpentine.
8.	British Guiana III.	Blue Mt Quarry. Demerara River. Quartz diorite dyke.
9.	Trinidad.	Maracas Valley. Quartzose talc schist.

(B) *Red soils derived from limestone.*

10.	Bermuda.	Exp. Station, Paget East. Shelly calcareous sandstone.
11.	Barbados.	Apes Hill Estate. Coral rock, containing andesitic ash.
12.	Anguilla.	Virgin Islands. Coralline and foraminiferal limestone.
13.	Jamaica.	Stony Hill. Foraminiferal limestone.

(C) *Kaolinitic soils and materials.*

14.	British Guiana kaolin 1 (bauxitic clay).	Trewern, Demerara River. British Guiana. Underlies bauxite. Said to be kaolin "leached from bauxite." Underburden, 30 ft. below ground level.
15.	Tobago kaolin.	Windward Coast cacao estates. Soft decomposed rock. Epidiorite (metamorphosed dolerite). May be partly gibbsitic.
16.	White bauxitic clay.	Same locality, and similar to No. 14.
17.	Red bauxitic clay.	Same locality as Nos. 14 and 16. Overburden of bauxite rock.
18.	Kaolinitic clay (T. and M.).	Commercial "colloidal clay." Purchased from Messrs Townsen and Mercer, London.
19.	Kaolin (B. and T.).	Commercial specimen. Purchased from Messrs Baird and Tatlock, London.
20.	British Guiana kaolin 2.	Kalacoon, Essequibo River. Decomposed aplite, highly kaolinised.
21.	Congo.	Bengala, Belgian Congo. Origin unknown.
22.	British Guiana kaolin 3.	Bartica, Essequibo River. Decomposed granite, highly kaolinised.

(D) *Other soils.*

23.	Barbados black (non-calcareous).	Carringtons Estate. Coral limestone. O.M. content 1·9 per cent.
24.	Antigua grey.	Tomlinsons Estate. Sedimentary andesitic tuff. Bentonite type.
25.	Dominica yellow.	Riversdale Estate. Hypersthene andesitic tuff. Rainfall, 150 in.
26.	Barbados yellow.	Forster Hall Estate, Scotland District. Sedimentary clay.
27.	Antigua chocolate.	Bendals Estate. Alluvium derived from andesite.

NOTE. (1) Samples Nos. 1, 11, 24, 26 and 27 are identical with or similar to those described in the earlier shrinkage paper (*J. Agric. Sci.* (1923), **13**, 243).

(2) Samples Nos. 1, 2, 6, 7, 9, 10, 11, 12, 15, 16, 18, 19, 20, 24, 25, 26 and 27 were used in the writer's investigation of sesquioxide components by alizarin adsorption (*J. Agric. Sci.* (1931), **21**, 150).

(3) Samples Nos. 4, 5, 8, 21 and 22, or very similar materials, were described in a paper on igneous rock soil profiles in British Guiana (Hardy and Follett-Smith, *J. Agric. Sci.* (1931), **21**, 739).

contents. For each soil, the approximate silica/sesquioxide molecular ratio, obtained by chemical analysis of the whole soil passing a 100-mm. mesh sieve, is given for purposes of characterisation, and, in addition, the loss (I) due to constitutional water liberated when the oven-dry soil is ignited, and the maximum uptake of moisture (R) and (H) when the material is exposed to atmospheres 50 and 96 per cent. saturated with water vapour are also presented. In each case, the results are expressed as percentages of the oven-dry weights of soil.

III. DISCUSSION OF THE DATA.

(Table II.)

(1) *Silica/sesquioxide molecular ratio.*

The values in column 1 indicate that most of the red soils approximate to lateritic types (ratio less than 2·0), but that certain of the materials classed as kaolinitic, notably the peculiar clays (Nos. 14, 16, 17) obtained from the bauxite mines of Demerara, might also be included under this head. The ratio values for kaolinitic materials vary within rather wide limits (between 2 and about 8), whilst the other materials (mainly "grey" soils) show values lying between 2·5 and 5·5. Since the ratio values were calculated from chemical analyses of the whole soils, and not the clay fractions nor the uncombined silica-free materials, they merely serve roughly to characterise the soils.

(2) *Interrelationships between water uptake at the sticky point (S); water uptake from a 50 per cent. saturated atmosphere (R) and loss on ignition (I).*

In the shrinkage determinations, the soils were worked up with water to the sticky point, and portions of the kneaded masses were used for making the prisms or blocks. Other portions were fashioned into cakes. From the weights of the initial moist and the final oven-dried pieces, the S values in column 5 were derived.

According to Keen and Coutts (7), S is very closely correlated with loss on ignition (I), and with the uptake of water from 50 per cent. aqueous atmosphere (R), particularly for humus-free soil. They maintain that it is reasonable to regard the constitutional water (represented by loss on ignition) as "related to the colloidal properties of the clay, and therefore to its reticulate structure, in which the equilibrium moisture content denoted by R is retained." Furthermore, they regard the moisture represented by S as also held by the colloidal material (which includes the inorganic colloids of the clay fraction), but they do not attempt to specify the particular manner in which the water occurring

	Soil constants				Shrinkage data						Ratio values				
	1 Ratio $\frac{SiO_2}{R_2O_3}$ (mol.)	2 Loss on ignition (I) % dry wt.	3 Water uptake, 50 % humid. (R) % dry wt.	4 Water uptake, 96 % humid. (H) % dry wt.	5 Total uptake of water (S) % dry wt.	6 Total shrinkage (T) % dry vol.	7 Residual water (d) % dry wt.	8 Residual shrinkage (t) % dry vol.	9 Pore space (P) % dry vol.	10 True Sp. Gr. (g)	11 S/I	12 $\frac{(S-16)}{I}$	13 $\frac{R}{I}$	14 S/T	15 $S-(16+d)$ $(=V)$ % dry wt.
(A) *Red soils derived from igneous rocks.*															
1. Dominica	1·6	12·9	12·1	17·1	63·5	55·9	29·6	4·5	41·0	2·61	4·92	3·63	0·94	1·14	17·9
2. Java	1·4	13·4	8·8	16·4	63·5	54·5	26·8	Nil	40·8	2·56	4·74	3·54	0·66	1·16	20·7
3. Grenada	1·9	12·9	6·8	14·5	50·4	54·7	21·3	2·0	35·0	2·68	3·91	2·66	0·53	0·92	13·1
4. British Guiana I	2·2	9·3	3·6	6·3	46·4	34·5	24·1	0·5	38·8	2·65	4·99	3·27	0·39	1·34	6·3
5. British Guiana II	1·9	13·2	4·9	7·6	46·1	34·4	25·3	1·2	39·6	2·67	3·49	2·28	0·37	1·34	4·8
6. Hawaii	1·3	13·7	6·9	11·4	44·8	35·7	24·1	0·5	39·2	2·70	3·27	2·10	0·50	1·25	4·7
7. Cuba (Nipe)	0·2	12·3	5·2	11·9	42·6	28·9	24·0	0·8	38·6	2·61	3·46	2·16	0·42	1·47	2·6
8. British Guiana III	2·7	8·6	3·9	5·9	32·6	26·5	17·4	Nil	30·0	2·46	3·79	1·93	0·45	1·23	−0·8
9. Trinidad	3·6	5·4	3·7	6·3	31·5	26·2	17·1	0·6	31·0	2·65	5·83	2·87	0·68	1·20	−1·6
										Means	4·26	2·72	0·56	1·23	—
(B) *Red soils derived from limestone (Terra Rossa).*															
10. Bermuda	1·0	19·1	12·4	17·5	62·2	36·1	31·7	1·8	41·4	2·33	3·25	2·42	0·65	1·72	14·5
11. Barbados	1·7	13·4	7·8	14·7	46·1	32·3	25·7	0·5	39·8	2·60	3·44	2·25	0·58	1·43	4·4
12. Anguilla	1·1	14·5	9·8	12·8	43·6	41·3	19·2	0·9	33·0	2·61	3·01	1·90	0·67	1·06	7·4
13. Jamaica	0·2	25·3	2·3	5·1	35·8	22·0	22·6	Nil	36·9	2·58	(1·41)	0·78	(0·09)	1·63	−2·8
										Means	3·37	1·84	0·63	1·46	—
(C) *Kaolinitic materials.*															
14. British Guiana kaolin 1	1·8	13·8	0·7	2·5	42·9	19·6	29·2	Nil	42·5	2·53	3·11	1·95	0·05	2·18	−2·3
15. Tobago kaolin	2·6	7·9	(5·5)	8·3	42·7	48·2	16·8	1·3	30·5	2·72	(5·41)	(3·38)	(0·69)	(0·88)	9·9
16. White bauxitic clay	1·0	21·0	0·7	1·1	41·8	16·5	28·9	Nil	41·2	2·42	2·00	1·23	0·03	2·53	−3·1
17. Red bauxitic clay	1·5	15·2	1·1	2·5	40·9	14·8	29·6	Nil	43·5	2·60	2·60	1·64	0·07	2·76	−4·7
18. Kaolinitic clay (T.M.)	2·0	10·3	3·6	4·7	39·9	33·0	20·2	Nil	33·5	2·50	3·87	2·32	0·35	1·21	3·7
19. Kaolin (B.T.)	2·0	12·0	0·8	1·9	39·5	20·6	25·4	Nil	39·3	2·54	3·29	1·96	0·07	1·92	−1·9
20. British Guiana kaolin 2	8·5	4·8	0·9	2·4	38·5	13·0	27·6	Nil	40·9	2·50	8·02	(4·69)	0·18	2·96	−5·1
21. Congo	8·3	3·9	1·0	1·5	24·1	15·3	16·9	1·5	30·4	2·71	6·18	2·08	0·26	1·57	−8·8
22. British Guiana kaolin 3	2·1	13·1	0·8	1·6	21·1	11·2	14·9	Nil	27·4	2·53	1·64	0·38	0·06	1·88	−9·8
										Means	4·01	2·18	0·13	2·13	—
(D) *Other soils.*															
23. Barbados black (non-calcareous)	2·4	13·2	9·4	14·3	51·5	76·1	15·9	6·8	25·0	2·65	3·90	2·69	0·71	0·68	19·6
24. Antigua grey	4·8	9·7	12·1	14·9	50·6	85·0	11·7	7·0	16·4	2·40	5·22	3·56	1·25	0·60	22·9
25. Dominica yellow	2·8	14·9	9·6	11·7	46·8	42·5	24·8	6·5	34·5	2·52	3·14	2·07	0·64	1·10	6·0
26. Barbados yellow	3·3	5·8	6·1	7·3	37·1	45·3	14·2	1·2	26·4	2·65	6·39	3·64	1·05	0·82	6·9
27. Antigua chocolate	5·6	6·9	6·3	8·8	36·1	44·1	15·5	5·1	25·1	2·60	5·23	2·91	0·91	0·82	4·6
										Means	4·77	2·98	0·91	0·80	—
(E) *Haines' soils (for comparison).*															
A. Clay separate	—	9·5	—	—	75·9	130·0	16·7	8·6	22·5	2·64	7·90	6·30	—	0·58	43·2
E. Harpenden	—	10·5	—	—	43·5	37·5	29·5	10·3	33·5	2·44	4·14	2·62	—	1·16	−2·0
C. Sudan clay	—	11·4	—	—	42·2	67·5	13·0	7·6	19·6	2·59	3·70	2·29	—	0·62	13·2
D. Durham subsoil	—	9·6	—	—	31·1	34·0	15·2	2·0	25·3	2·64	3·24	1·57	—	0·91	−0·1
F. Rothamsted loam	—	8·3	—	—	28·4	21·0	18·7	2·2	30·3	2·57	3·42	1·49	—	1·35	−4·3
B. Kaolin	—	12·4	—	—	45·2	30·0	24·8	Nil	37·8	2·45	3·64	2·35	—	1·51	4·4

in these different states is related to or bound up with the mineral colloidal material.

If we accept the micro-reticulate structure hypothesis due to Wilsdon (2), it would appear that *R* represents adsorbed or surface-combined water, and *S* represents surface-combined water at saturation equilibrium (*H*) (which includes *R*) *plus* water held in the vesicles of the micro-reticulum, *plus* a certain amount of water held in the minute interstices and capillaries occurring between colloidal clay particles or colloid-coated soil grains. Keen and Coutts' results indicate that ((7), p. 754) this latter (interstitial) quantity, over a fairly wide range of soils, approximates to 16 per cent. of the oven-dry weight of the soil. The writer had previously suggested (8) that interstitial water might be evaluated as 20 per cent. of the sand content of the soil, on the assumptions that a sand-free colloidal clay, kneaded with water, contains very little interstitial water, whereas a colloid-free sand, wetted to a coherent mass, contains all its water as interstitial films and wedges.

From the data in column 11, it will be noticed that *S* and *I* are closely correlated for all the soil types, and that the ratio value *S*/*I* possesses approximately the same mean magnitude for each of the soil classes (namely, 4·26, 3·37, 4·01 and 4·77; weighted average, 4·17). The mean value of this ratio for Keen and Coutts' soils (7) is 6·45, and for Coutts' South African soils (9), 3·72, the differences in magnitude being partly due to the facts that, in the first case, the soils contained appreciable ignitable organic matter, and in the second, the data were based on air-dry and not oven-dry weights. The soils examined in the present investigation, with few exceptions, are devoid of organic matter, but contain variable amounts of coarse and fine sand. When *S* values are corrected for interstitial water (which, according to Keen and Coutts, approximates to the constant 16), the ratio of ($S - 16$) to *I* (column 12) deviates for the four soil classes, being lowest for the red limestone soils and the kaolinitic materials. Furthermore, when *R* values are compared with *I*, the ratio *R*/*I* (column 13) is clearly the lowest for the kaolinitic materials, because the uptake of water from a 50 per cent. saturated aqueous atmosphere (column 3) is typically very small for these materials.

The possible significance of these relationships and differences will be considered in a later section.

(3) *Interrelationship between shrinkage* (*T and t*) *and water uptake* (*S, d and R*).

As in the earlier shrinkage investigation, the ratio values for *S*/*T* (column 14) indicate a significant difference between the red soils

(A and B) and the grey soils (D), being much greater in the case of the red soils (1·23 and 1·46 against 0·80). The kaolinitic materials show the lowest relative shrinkages of all; they evidently resemble the red soils in this respect. Moreover, the red soils and the kaolinitic materials[1] exhibit relatively small or no *residual* shrinkage, whereas the grey soils show very marked residual shrinkage.

These results may be interpreted in terms of the structure theory(1) of soil colloidal material which is based on certain premises, namely, (1) that normal shrinkage is due to the uniform loss of water from interstices and capillaries (representing, according to Keen and Coutts, about 16 per cent. of the dry weight of the soil), and from the vesicles of the colloid micro-reticulum; (2) that residual shrinkage (or shrinkage lag) sets in when the rigidity of the micro-reticulum begins to oppose its further collapse, so that loss of residual water is not accompanied by a comparable diminution in soil volume; (3) that a portion of the residual water is held in close association with (*i.e.* is adsorbed by) the micellar material that forms the walls or framework of the colloid micro-reticulum, and (4) that the colloidal components of widely different soil types exhibit differences with respect to (*a*) dimensions (size and shape of vesicles), (*b*) rigidity, and (*c*) physico-chemical composition and properties of the micellar material.

Based on these ideas, sticky-point water (S) is made up of four more or less distinct portions, namely: (i) *interstitial water* (approximately constant and equal to 16 per cent. over a considerable range of soils); *vesicular water* (ii) whose partial loss (V) is accompanied by uniform normal shrinkage, (iii) whose further loss (v) is accompanied by diminishing residual shrinkage; and (iv) *adsorbed water* whose loss is not accompanied by shrinkage. The last portion, according to Wilsdon, approximates to the indefinite hygroscopic coefficient stage (H); it includes moisture taken up by dry soil from aqueous atmospheres (for example, at 50 per cent. humidity (R)). According to Keen and Coutts, it is closely linked with *water of constitution*, occurring in the micellar material whose degree of hydration may differ somewhat in different types of soil. Hence, $S=16+V+v+H$.

At the point when normal shrinkage gives place to residual shrinkage, the free-water content (v) of the vesicular spaces (into which air is beginning to gain access) is evaluated by $(d-H)$. In those cases where no residual shrinkage occurs (for example, the kaolinitic materials), presumably the vesicular spaces have already completely collapsed (so that here $v=0$, and $d=H$), or else the water-holding structure is not vesicular at all, and normal shrinkage is entirely due to loss of interstitial water. In column 15 (Table II), values for $S-(16+d)$ are presented. The recorded values should furnish a measure of V, the free vesicular water whose loss is accompanied by part of the normal shrinkage. It will be noted that, for the kaolinitic materials, the values for V are generally negative, which suggests that they owe their shrinkage, not partly to vesicular water, but *entirely* to loss of interstitial water (*i.e.* $d=S-16$).

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[1] Among Haines' soils, the Rothamsted loam, derived from chalk, resembles kaolin in its low relative total shrinkage (high S/T ratio). This is interesting in view of the fact that Marshall has shown that Rothamsted soil exhibits similar optical properties to kaolin(10), but resembles beidellite in its dispersion phenomena(11). This soil has been the subject of numerous experimental researches, generalisation from which might therefore require reinterpretation in the light of this finding.

It would thus appear that an attempt to apply the structure theory of shrinkage to kaolinitic materials completely breaks down in two particulars, namely, (1) that their shrinkage seems to be due solely to loss of interstitial water (since their residual moisture contents (d) are generally equal to or slightly greater than $(S-16)$), and (2) that their hygroscopic coefficients (H) (as represented by water uptake from 96 per cent. saturated atmosphere—column 4) appear to be far too small to account for the relatively high residual moisture contents at the cessation of shrinkage (column 7).

Hygroscopic coefficient. The assumed significance and the validity of experimental results obtained in attempts to measure hygroscopic coefficients by uptake of water from a saturated aqueous atmosphere have recently been seriously doubted (12, 13, 14). The uptake from atmospheres above 95 per cent. saturation by water vapour is very much greater than that in the region of 50–70 per cent.; the hyperbolic vapour-pressure curves above 95 per cent. are almost horizontal, indicating slow continued uptake, until the soil interstices become completely filled. Moreover, the vapour pressure of wet soils that are drying remains constant throughout a considerable range of moisture content before it slowly decreases (6, 15). Hence, it is evident that the value for H obtained by the usual humidifier method may be considerably lower than the value actually representing the maximum amount of water that may be retained as surface-adsorbed films when wet soil is slowly dried. The discrepancy in the determined values for H, depending on the direction of experimental approach (*i.e.* whether from the moist or from the dry state), may possibly depend on the physical composition of the soil, particularly with regard to the presence or absence of a micro-reticulate structure in its finer-grained components. The discrepancy may be particularly large for those materials in which structured colloidal matter is absent, as appears to be the case in kaolin[1]. In kaolinitic materials, surface adsorptive properties are known to be lacking, the component particles being chemically inert, and showing low base-exchange capacity. In other types of clay, to which the structure theory of shrinkage and water uptake seems closely to apply, the difference between the values for H as determined firstly by exposing the soil to a saturated aqueous atmosphere, and secondly by drying the wet soil and measuring the rate of fall of vapour pressure, does not appear to be so great; consistency in the determination of H values by the humidifier method is usually readily attainable in these cases.

IV. CLAY TYPES; KAOLINITIC AND NON-KAOLINITIC CLAYS AND SOILS.

The foregoing experimental results and conclusions suggest that kaolinitic clays and soils differ fundamentally from colloidal mineral materials that exhibit marked total and residual shrinkage, as, for example, "grey" soils, derived mainly from aqueous sedimentary rocks. The data obtained for tropical red soils, both those produced from basic igneous rocks and those derived from limestone, indicate that these types are *intermediate* in their attributes. The main qualitative results are summarised in the accompanying scheme, which is based on results roughly recalculated to allow for variations in sand content.

General comparison between kaolinitic materials, red soils and grey soils.

		Red soils		
	Kaolinitic materials	*Derived from igneous rocks*	*Derived from limestone*	*Grey soils*
Loss on ignition (I)	Medium low	Medium high	High	High
Water uptake, 50 % (R)	Very low	Medium low	High	Medium high
Sticky point (S)	Medium	High	High	Medium high
Residual water (d)	Medium high	Medium high	Medium high	Low
Total shrinkage (T)	Low	Medium low	Medium low	Very high
Residual shrinkage (t)	Nil	Low	Low	High
Vesicular shrinkage water (V) $= S - (16 + d)$	Nil	Medium low, but variable	Medium low, but variable	High
Pore space (P)	High	Medium high	Medium high	Low
S/I	Medium	Medium	Medium	Medium
R/I	Very low	Medium low	Medium low	High
S/T	Very high	Medium high	Medium high	Very low

It would appear from this comparison that most of the physical attributes and peculiarities of tropical red soils (which impart characteristic field properties to them (16)), may be explained on the assumption that *they contain kaolinitic mineral substances among their colloidal components*[1], and that these may be sufficiently dominant to control their water relations and cohesiveness. The apparent absence of appreciable quantities of free hydrous alumina and free hydrous ferric oxide (17) from the majority of tropical red soils (usually classified as red earths and red loams that do not belong to the true "laterite" class), indicates that these entities may play subsidiary parts in the manifestation of many of their physical properties. Sufficient is not yet known, however, to enable one to assess the effects of these subsidiary components of red soils.

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[1] The *hygroscopic coefficient* values (H) for kaolinitic materials set out in Table II were determined by exposure to a 96 per cent. humid atmosphere at 28° C. for *seven days*. On repeating the determinations for an extended period (three months), greatly increased values were obtained. The ratio between the second and first set of H values ranged from 2·3 to 9·3, average about 5·0, indicating continued uptake of water of considerable magnitude.

Clay minerals. The fact that the clay fraction of different types of soil varies considerably in structure is becoming increasingly recognised as a result of X-ray and optical examination. The structural elements (micelles) are apparently crystalline, and they may be associated into gels or emulsoid colloids possessing definite vesicles. Attrition and mechanical dispersion may partly disintegrate naturally formed micellar systems, causing a separation of colloidal matter consisting of structural units having microscopic dimensions.

Recently, Hendricks and Fry (18) have identified the crystalline matter comprising the colloidal components isolated from a wide range of soils. They recognise three chief types of clay, namely, montmorillonite, halloysite and potash bentonite (which may consist, however, of montmorillonite and quartz). Samples of red soil, having very low silica/sesquioxide ratios, proved to contain bauxite (gibbsite?), but most of the highly ferruginous soils examined apparently contained clay minerals of the halloysite type. Kelley, Dore and Brown (19) have similarly identified potash bentonite in certain American soils, and have suggested that its chief mineral entity, namely montmorillonite, represents the first product of the chemical weathering of silicate minerals. Marshall (20) has presented a tentative classification of clay minerals according to the following (abridged) scheme:

(A) *Hydrated alumino-silicates.*	
(1) *Showing base-exchange properties.*	
Montmorillonite	($MgCaO.Al_2O_3.5SiO_2.nH_2O$).
(2) *Not showing base-exchange properties.*	
(*a*) Kaolins (Kaolinite, Dickite, Nacrite)	($Al_2O_3.2SiO_2.2H_2O$).
(*b*) Halloysite	($Al_2O_3.2SiO_2.3H_2O$).
(*c*) Beidellite (Leverrierite)	($Al_2O_3.3SiO_2.3H_2O$).
(*d*) Pyrophyllite	($Al_2O_3.4SiO_2.H_2O$).
(B) *Hydrated ferro-silicates.*	
Nontronite	($Fe_2O_3.3SiO_2.2H_2O$).

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[1] Many years ago, the late Sir John Harrison identified by petrographical means kaolinite and halloysite in certain red earth profiles overlying basic and intermediate igneous rocks in British Guiana (22). The methods then available were not so refined as those nowadays used for the investigation of clay minerals (20).

By "base exchange," as applied to these minerals, is meant reversible reactions of the zeolitic type, in which replacement of one cation by another is accompanied by a definite change in the density and optical properties of the crystal. This result is due to the fact that the cations occupy specific positions within the lattice, access to which is afforded through channels filled with water molecules. The capacity for such base exchange is not affected by degree of dispersion, and is much greater and more profound than that exhibited at a surface double-layer which operates in the more general type of replacement processes. Zeolites (and permutites) give no characteristic X-ray pattern. Bentonite is a sedimentary rock derived from volcanic ash or tuff. It owes its characteristic colloidal properties to the presence of montmorillonite or of beidellite, both types of bentonite being recognisable. Kaolin minerals show the greatest tendency to form definite crystals. Kaolinite is apparently very rare in soils (21); its origin is generally pneumatolytic. Halloysite, anauxite, and especially beidellite, are much more common soil minerals. Montmorillonite contains more constitutional water[1] and possesses a greater water-absorption capacity than the kaolins (21); it occurs in bentonite as groups of crystalline plates, resembling sericitic mica, and is also present in fuller's earth.

Although many of the chief features and relationships of certain clay minerals seem to have been established, there is a great need of further information concerning them. Doubtless this will be forthcoming when modern X-ray and optical analysis has been applied to a wider range of samples. In particular, tropical red soils deserve examination by these methods, since many of them represent the products of direct weathering of igneous rocks. Their profiles are often very deep, so that typical samples of all the stages of soil formation may readily be obtained (22). As Robinson justly remarks (23): "It is to be regretted that most of the investigations by X-ray methods hitherto conducted have been on soils of secondary weathering. Results from soils formed by direct weathering of crystalline rocks would be of the highest interest and significance in elucidating the nature of the process of clay formation."

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[1] In accordance with this fact, clays whose characteristic mineral is montmorillonite should exhibit relatively high losses on ignition, as well as a high water-adsorbing capacity (($S - 16$) values, H values and R values) when compared with clays belonging to the kaolin-beidellite class.

V. SUMMARY.

1. This article describes the comparative results of the determination of shrinkage constants (Haines' method) and of certain soil moisture constants for a series of clay soils representative of three important classes, namely, *tropical red soils* derived from igneous rocks and from limestone, *kaolinitic soils* and materials, and *grey and yellow soils*, mainly derived from aqueous sedimentary rocks.

2. An attempt is made to interpret the data in terms of Wilsdon's micro-reticular hypothesis of soil colloidal structure, and to explain the physical significance of some of the constants measured, particularly sticky point moisture (S), loss on ignition (I), water uptake from aqueous vapour (H, R), and Haines' "residual shrinkage" moisture content (d).

3. The results indicate that *tropical red soils closely resemble kaolinitic materials in their shrinkage behaviour and moisture relations*, but that they are intermediate between this type and grey and yellow soils, which exhibit characteristic high total shrinkage, marked residual shrinkage and high adsorptive capacity for moisture and for cations.

4. A brief review of recent literature concerning the mineralogy of clay minerals (based on X-ray analysis and optical examination) is offered in support of these findings.

5. The need of detailed mineralogical investigations of the products of weathering of rocks under humid tropical conditions is urged. Such study might reveal the causes of the characteristic and peculiar field properties of tropical red soils which appear to have been neglected by soil physical-chemists.

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THE FORMATION, EVOLUTION, RECLAMATION, AND THE ABSORBED BASES OF ALKALI SOILS.

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INTRODUCTION.

As is well known, alkali soils occur chiefly in regions of limited precipitation. Many years ago Hilgard became impressed with this fact. In his well-known book on *Soils* (12), Hilgard developed the view that the soluble salts of soils and of natural waters are formed by the weathering of rocks and minerals. In humid climates the soluble products of weathering are leached into the underdrainage and out to the sea, whereas under conditions of limited rainfall the soluble products accumulate, to some extent at least, within the boundaries of a given drainage basin. De 'Sigmond (20, 23) holds that the process of actual accumulation of soluble salts in the soil must involve either a period of overflow and inundation with the soil having a more or less impervious substratum, or else the development of a high-water table from which the soluble salts can arise by capillarity. Hilgard also recognised the importance of these conditions.

The weathering of igneous rocks probably does not proceed at once to the relatively stable end products of weathering, which are soluble salts, iron and aluminium oxides, silica, and the clay minerals[1]. Rather, igneous minerals undoubtedly pass through a series of intermediate stages of alteration, which fact is generally recognised by geologists and mineralogists. Various compounds of indefinite and vaguely understood composition are probably formed by the weathering of igneous rocks.

If, then, the most soluble products of weathering, namely, chlorides, sulphates, carbonates and bicarbonates, accumulate here and there in the soils of arid regions, it is obvious that the less soluble products of weathering may also accumulate in the soil to some extent. Hilgard recognised this fact, for he pointed out that arid soils in general contain much greater amounts of acid-soluble silicates than do the soils of humid climates. From the standpoint of the soil, the best-known example of a substance of intermediate solubility is $CaCO_3$.

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[1] This statement should not be interpreted to mean that the clay minerals are necessarily unchangeable. There is considerable evidence that the stability of the different clay minerals is influenced by the *p*H of the medium. Under alkaline conditions clays of relatively high SiO_2 content appear to be formed. Later, if intensive leaching conditions persist, these may gradually lose SiO_2 and thus be converted into other clay minerals, and finally be decomposed into simple oxides.

Under conditions where the soluble salts become concentrated through the evaporation of solutions that have drained away from weathering masses of certain kinds of igneous rocks, it seems reasonable to assume that more or less silicate of calcium and magnesium will be precipitated in the soil since, upon evaporation, calcium and magnesium, dissolved by weathering, should combine to some extent with dissolved SiO_3 ions, which have arisen, either directly as one of the products of weathering, or have been formed by the interaction of Na_2CO_3 and colloidal SiO_2. It is obvious that both the absolute and relative amounts of the various products that are formed by weathering, or by precipitation, will depend on the kind of materials that undergo weathering and on the conditions under which the weathering process, and the accumulation of the soluble products thereof, take place. The author believes that these facts have an important bearing on certain phases of alkali soils. This point will be more fully discussed in another section of this paper.

Hilgard held that soluble salts are themselves directly responsible for the unfavourable properties of alkali soils, and that by removing the soluble salts, alkali soil will be converted into normal soil. He apparently believed that the solid phase of soils is inert toward the soluble salts which accumulate in alkali soils. However, extensive investigations on base exchange, begun originally by Way(21), and more fully developed during the past two decades by several investigators, have fully established the fact that certain of the solid constituents of soil are not inert toward soluble salts. We now know that sodium salts tend to react with the base-exchange substances of soils with the consequent formation of Na-absorption compounds and the replacement of cations, chiefly calcium. Thus NaCl replaces calcium, whereby the sodium is absorbed and $CaCl_2$ is formed. Upon leaching the soil, the $CaCl_2$ thus formed is carried away, leaving the absorbed sodium in the soil. Furthermore, if important amounts of sodium have been absorbed by the soil, its physical and chemical properties are profoundly influenced by the same. Therefore, the mere removal of the soluble salts does not necessarily convert an alkali soil into a normal condition[1].

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[1] Hilgard's failure to recognise the importance of base exchange in alkali soils is difficult to explain, since he placed strong emphasis on the base-exchange property of the so-called zeolites of soils, and since he pointed out (12), pp. 38, 268) that calcium

The extent to which the base-exchange complex of the soil has undergone cation exchange by reacting with soluble salts, depends largely on the concentration and composition of the soluble salts that have accumulated in it, and on the amount of exchangeable cations that are held by the soil (15). If sodium salts comprise a sufficiently high percentage of the total soluble salts of the soil, a high percentage of the base-exchange complex will have been converted into Na-absorption compounds. On the other hand, soluble calcium salts tend to prevent the formation of Na-absorption compounds. Moreover, the replacing power of calcium exceeds that of sodium. If a comparatively high concentration of soluble calcium salts be present, Na-absorption compounds will not be formed, even though a high concentration of sodium salts be present in the soil. Thus the ratio of soluble sodium to soluble calcium has an important influence on base exchange and consequently on the properties of alkali soils. The base-exchange reaction of soils is completely reversible; hence Na-absorption compounds can be reconverted back into the corresponding calcium compounds by applying a soluble calcium salt.

THE EFFECT OF BASE EXCHANGE.

The formation of Na-absorption compounds in soils may lead to a series of extremely important consequences. These can best be considered under three heads, namely, chemical, physical and evolutionary.

From a chemical standpoint Na-absorption compounds exert the greatest effect on the soil through their influence on the *p*H concentration of the soil. These compounds, or complexes, as they are commonly called, tend to undergo hydrolysis in water. The result is that soils containing relatively much absorbed sodium usually become alkaline upon leaching, sometimes highly so. The extent to which hydrolysis will take place depends upon the amount of absorbed sodium and the concentration of the sodium salts that are present. As long as a relatively high concentration of soluble sodium salts is present, hydrolysis of the Na-absorption complex will not take place owing to the well-known common-ion effect but, upon leaching, NaOH is formed which becomes converted into Na_2CO_3 and $NaHCO_3$ by the CO_2 of the soil.

As early as 1888 Mondesir (17) showed that Na_2CO_3 may be formed

and potassium of certain zeolites, and potassium of leucite, can be replaced by sodium by leaching the same with a solution of NaCl. The fact that NaCl is by far the most abundant salt in sea water and that sodium is held less tenaciously by soils than the other bases, probably influenced his conclusion. Whatever be the correct explanation of Hilgard's views, the author has been unable to find any reference in his publications to the occurrence of replaceable sodium in alkali soils.

in soils in consequence of cation exchange. He exhibited before the French Academy of Sciences 100 gm. of trona ($Na_2CO_3.NaHCO_3.2H_2O$) which he had prepared by leaching 1 kg. of calcareous soil twenty times with a solution of NaCl, then with water, and finally with carbonated water. He pointed out that the sodium of NaCl replaced calcium from the soil; upon leaching with carbonated water $CaCO_3$ was dissolved and the Ca ions thus formed then replaced sodium from the soil, thus forming Na_2CO_3. Upon repeating these processes, additional amounts of Na_2CO_3 will continue to be formed as long as the soil contains $CaCO_3$. As will be shown later, these results of Mondesir lie at the foundation of an important method of alkali-soil reclamation.

The principles on which the results of Mondesir were based have been extensively investigated by Gedroiz(4), de 'Sigmond(19, 21), Dominicis(3), Prescott(18), and Cummins and Kelley(2). It is now well established that, upon leaching a sodium saline soil with water, Na_2CO_3 is formed. Cummins and Kelley showed that the formation of Na-absorption compounds may lead to the production of Na_2CO_3, either in the presence or the absence of $CaCO_3$. If $CaCO_3$ be absent from the soil, the Na-absorption compounds (Na clays and Na humates) undergo more or less hydrolysis upon leaching, with the resulting formation of NaOH and of H-absorption compounds (base unsaturated soil). Carbon dioxide of the soil then converts NaOH into Na_2CO_3. In the presence of $CaCO_3$ much greater amounts of Na_2CO_3 will be formed, but in this case the H-absorption compounds will react with $CaCO_3$, thus forming Ca-absorption compounds. As will be shown later, advantage may be taken of this fact as a means of reclaiming alkali soil.

The physical properties of the soil are also markedly affected by the replacement of the normal bases of the soil by sodium. As sodium replaced calcium from the base-exchange complex, the dispersability of the colloidal particles of the soil is greatly increased. This dispersion does not take place as long as a high concentration of soluble salts remains in the soil, owing to the coagulating effect of soluble electrolytes, but upon leaching a point is soon reached where pronounced dispersion manifests itself. Gedroiz(7) has shown that the ultra-mechanical composition of the soil is markedly influenced by treatment with a solution of NaCl followed by leaching with water. As a result of treatments of this kind, particles of extremely small diameter appear to be formed at the expense of the aggregates that usually occur in normal soils. According to Gedroiz(11) and Wiegner(25), the dispersing agent in such cases is the OH ion that is formed by hydrolysis.

Dispersion begins to manifest itself when only a small amount of Na-absorption compounds has been formed. We have found, for example, that a single application of a soluble sodium salt, applied at the rate of only a few hundred pounds per acre, may produce substantial lowering of the leaching rate of the soil, even without there being any measurable change in the OH-ion concentration of the soil. In the opinion of the author a satisfactory explanation of this fact cannot now be given. In any case the physical effects of base exchange are of great importance. The relative impermeability of sodium soils is one of their striking characteristics and this impermeability adds great difficulty to tillage operations, the preparation of a suitable seed bed, and to the reclamation process. Gedroiz (8) has shown that the effect of Na-absorption compounds on the ultra-mechanical composition of the soil leads to the development of the so-called solonetz structures.

THE EVOLUTION OF ALKALI SOILS.

Gedroiz (8) fully discussed the various influences of Na-absorption compounds on the genetics of alkali soils. De 'Sigmond (23) has recently emphasised the dynamic aspects of alkali soils. He pointed out that the evolution of alkali soils may be considered as taking place in four stages, namely, salinisation, alkalinisation, desalinisation, and degradation.

Salinisation obviously denotes the process of soluble salt accumulation as such. *Alkalinisation* refers to the formation of Na-absorption compounds through base exchange. As a matter of fact the so-called alkalinisation of the absorbing complex of the soil takes place concurrently with the salinisation process. This must be true, since the accumulation of soluble salts in soils is a gradual process, in most cases at least, and since it is well established that the rate of the base-exchange reaction is extremely rapid. It is certain that more or less alkalinisation of the absorbing complex takes place immediately upon contact between the soluble salts and the soil. However, it is extremely important to understand that the mere accumulation of soluble salts in the soil is not the only important aspect of alkali soils. It was the failure to recognise the fact that soluble sodium salts react with the base-exchange complex of the soil that imposed the chief limitation on Hilgard's comprehension of alkali soils.

Alkalinisation of the soil may even take place, as Gedroiz (9) has pointed out, without the accumulation of a high concentration of sodium salts. For example, if a dilute solution of NaCl be percolated through a column of soil for a long period, a high percentage of its absorbed bases will be replaced by sodium. The presence of Na_2CO_3 in the leaching solution will accentuate the formation of Na-absorption compounds. It follows, then, that the so-called alkalinisation process is not necessarily dependent on a high degree of salinisation of the soil, the occurrence of an impervious layer in the subsoil, or the capillary rise of sodium salts. In situations where the soil is subjected to intermittent overflow, for a relatively long period, of drainage waters that contain a low concentration of sodium salts, the soil may become pronouncedly alkalinised even though the solutions should drain away rapidly.

It is also important to emphasise the fact that alkalinisation of the absorption complex of the soil is greatly influenced by the composition of the soluble salts. As stated already, the presence of soluble calcium salts tends to prevent the formation of Na-absorption compounds. If the soluble salts that accumulate in the soil contain a high proportion of calcium in relation to sodium, alkalinisation will not take place at all ((15), p. 485). There are many important areas of alkali soil in America that contain no more than negligible amounts of absorbed sodium. Such soils always contain a high content of soluble calcium salts.

Desalinisation refers to the leaching process to which alkali soils are subjected in the state of nature. As suggested above, Gedroiz (8, 9, 11) discussed this aspect of the subject at considerable length. It is convenient to consider the desalinisation process as taking place in three steps, (*a*) the removal of the soluble salts, (*b*) the formation of Na_2CO_3 through hydrolysis of the absorption complex, either in the presence or absence of $CaCO_3$, (*c*) the dispersion of the soil particles with the consequent elutriation downward of the finely divided colloidal particles, thus giving rise to dense subsoil horizons.

Degradation refers to the decomposition of the absorbing complex of the soil, which is thought to be the consequence of prolonged leaching of soils that contain relatively much absorbed sodium. This process is analogous to podsolisation in that more or less of the absorbed bases of the soil are replaced by H ions in both processes, but degraded alkali soils differ from podsol soils in two important particulars, namely, (*a*) the former contain relatively much absorbed sodium, whereas the latter contain almost no absorbed sodium, (*b*) the absorption complex tends to undergo decomposition as a result of both degradation and podsolisation, with the consequent formation of colloidal SiO_2; but, according to Gedroiz (8), SiO_2 of silicates is leached out of podsol soils, while it tends to accumulate in degraded alkali soils.

As to whether or not decomposition of the absorbing complex, that is degradation, will take place as a result of prolonged leaching, depends on the composition of the insoluble constituents of the soil. Gedroiz(9) pointed out that the presence of $CaCO_3$ tends to protect the inorganic-absorption complex of the soil from decomposition during the leaching process, that under these conditions the absorbed sodium will be replaced, in part at least, by calcium with the consequent formation of stable, Ca-absorption complexes. In the opinion of the author, the inorganic-absorption compounds of the soil will undergo no important amount of decomposition as a result of leaching if $CaCO_3$ be thoroughly disseminated throughout the soil, since H-absorption compounds, the formation of which represents the first step in the degradation process, are very reactive towards $CaCO_3$. This reactivity leads at once to the formation of stable, Ca-absorption compounds (Ca clays). However, sodium soils will sustain more or less loss of organic constituents as a result of leaching, owing to the relatively high solubility and instability of organic, Na-absorption compounds, but the presence of $CaCO_3$ reduces the loss of these constituents materially.

Thus it follows that the evolution of alkalinised soils into the degraded (solod) condition will depend either on the composition of the soil before salinisation began, or else on the composition of the constituents which have been transported to the soil during the salinisation stage. Under certain conditions $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$ constitute substantial percentages of the soluble salts that are transported to the soil through inundation by or overflow of drainage waters. For example, in the case of the Salt Lake area of Utah, which is flanked on the east by a range of mountains that contain large amounts of limestone and dolomite, the run-off from these formations deposits calcium and magnesium carbonates upon evaporation. When leached, the sodium clays that have been formed in this soil as a result of the accumulation of high concentrations of sodium salts, will react with these carbonates; consequently the absorbed sodium of the soil will ultimately become replaced by calcium and magnesium. Hence the degradation stage will not be produced in this soil, however much it may be leached. In general it may be said that degradation (solodisation) will probably never become important in the vast majority of the alkali soils of the American continent, because $CaCO_3$ is almost universally present in these soils.

Obviously the sequence of the above-named processes may be interrupted through (*a*) alteration in the climatic conditions, or (*b*) modification in the elevation of the soil with respect to the surrounding areas.

Thus if soluble salts should accumulate in the soil after more or less desalinisation has taken place, the soil is said to become *regraded*(23) alkali soil.

It is clear from the foregoing that the reclamation of alkali soils must involve two interrelated, yet essentially different processes, namely, the removal of the excess of soluble salts, and the replacement of absorbed sodium by calcium. Of course, should a given alkali soil be deficient in any necessary plant food constituent, it may also be necessary to apply some fertiliser, or should the soil conditions be adverse because of any other unfavourable circumstances, profitable crops may not be obtained from it even after the soluble salts and the absorbed sodium have been removed, but these matters are not to be considered as aspects of the alkali problem as such.

The removal of soluble salts can be accomplished in a practical way only by leaching, and in order to leach the soil effectively the drainage conditions must be favourable and the soil must be sufficiently porous to permit water to pass through it. The physical effects produced by absorbed sodium may seriously interfere with the leaching process, but, as will be shown below, this is not the case with certain types of sodium soil.

THE RECLAMATION OF ALKALINISED SOIL.

In connection with our investigations on the alkali soils of California we have demonstrated the value of gypsum, sulphur, and leaching as treatments for sodium soil. The experiments were made near Fresno, California, on an area that is representative of a large body of alkali soil. This soil is a fine sandy loam low in organic matter. It is quite uniform in texture down to a depth of about 2½ ft., below which there is a layer, varying in thickness from 2 to 6 in., which contains about 10 per cent. $CaCO_3$. This calcareous layer rests on sandy loam material of considerable depth similar to that of the surface soil. The original soil of the experimental plots contained a relatively high concentration of soluble salts, absorbed sodium to the extent of about 65 per cent. of the total replaceable bases, and about 0·1 per cent. $CaCO_3$. It is therefore a mildly calcareous, Na-solonchak soil. From an evolutionary standpoint this alkali soil has passed into the so-called alkalinisation stage.

Effect of gypsum. In one of numerous experiments gypsum was applied in 1920 at the rate of 9 tons per acre and again in 1921 at the rate of 6 tons per acre. After each application of gypsum the experimental area was flooded with water for periods of about 3 weeks each, the object being to leach out the soluble salts and to effect the penetration of the gypsum into the subsoil. Subsequently the soil has been cultivated, ploughed, cropped, and irrigated according to methods that are in common use in California. Irrigation water has been applied somewhat more frequently than is usually done in California, the object being to maintain relatively high dilution of the soil solution and to effect more or less continual downward movement of soluble electrolytes. The water applied as irrigation has itself produced some leaching of the soil. However, the periods of flooding, referred to above, resulted in the removal from the soil of a high percentage of the soluble salts.

Table I. *Distribution of water-soluble and exchangeable bases in the gypsum plot of the Fresno experiment.*

Milliequivalents per 100 gm. dry soil

Depth in in.	Water-soluble				Exchangeable				Na as % of total	*p*H
	Ca	Mg	K	Na	Ca + Mg	K	Na	Total		
Before treatment (1920).										
0–12	Trace	Trace	0·20	2·16	1·08	0·23	3·13	4·44	70	9·67
12–24	,,	,,	0·20	1·47	0·42	0·98	2·87	4·27	67	9·42
24–36	,,	,,	0·21	1·09	1·78	0·28	2·41	4·47	54	9·59
36–48	,,	,,	0·18	0·82	2·57	0·34	1·59	4·50	35	9·11
After treatment (1931).										
0–12	0·23	Trace	Trace	0·24	5·25	0	0·27	5·23	5	7·53
12–24	0·17	,,	,,	0·27	4·59	0	0·40	4·99	8	8·10
24–36	0·12	,,	,,	0·50	4·63	0	0·43	5·06	8	8·30
36–48	0·07	,,	,,	0·67	4·13	0	1·00	5·13	19	8·70

The data presented as Table I show the results that have been produced by the combined effect of gypsum and leaching. It will be noted that the soluble salts and absorbed sodium have been chiefly removed from this plot to a depth of at least 48 in. In 1928 Kelley and Arany (13) published a report based in part on a comparative study of samples drawn from this plot before the experiment was begun and samples drawn in 1926. It was shown that, although the principal part of the soluble salts had been removed from the soil, it still contained considerable absorbed sodium. The samples drawn in 1931 show that a high percentage of the remaining absorbed sodium has finally been removed. In the meantime large yields of alfalfa, cotton and oats have been harvested from this plot.

Effect of sulphur. The data reported in Table II show the effects that have been produced by sulphur applied in 1921 at the rate of 3600 lb. per acre. It will be noted that sulphur and gypsum have produced very similar effects. There is, however, an important difference between the effects of gypsum and sulphur that should be mentioned, namely, gypsum produces its effect through the soluble calcium which it contains, whereas sulphur is effective because it brings about the solution of $CaCO_3$. As was pointed out previously (13) sulphur, upon oxidation, becomes converted into H_2SO_4, which then reacts with the carbonates of the soil. The calcium thus dissolved reacts with the Na-absorption compounds converting the same into Ca-absorption compounds. This explanation has been confirmed by determination of the insoluble carbonate of the soil (see Table IV).

Effect of leaching. Several check plots were also included in these experiments, to which no gypsum, sulphur, or other soil amendment has been applied. These plots have been flooded with water, irrigated, and cultivated like the gypsum and sulphur plots. As Kelley and Thomas (16) pointed out in 1928, the check plots produced inferior yields of crops for several years after the experiments were begun. In fact certain spots within the check plots remained totally unproductive for several years. Gedroiz (9) has stated that leaching an alkali soil, similar to that of these experiments, will prove to be an unsuccessful method of reclamation, owing to the fact that Na_2CO_3 will continue to be formed, with the attendant deflocculation of the soil. However, we have found that from year to year the most unproductive spots within the check plots have gradually diminished in size without applying any amendment to the soil. These spots finally disappeared entirely in 1928. Subsequently large yields of alfalfa, cotton and oats have been obtained from all parts of the check plots.

Table II. *Distribution of water-soluble and exchangeable bases in the sulphur plot of the Fresno experiment.*

	Millicquivalents per 100 gm. dry soil									
	Water-soluble				Exchangeable					
Depth in in.	Ca	Mg	K	Na	Ca + Mg	K	Na	Total	Na as % of total	*p*H
					Before treatment (1921).					
0-12	Trace	Trace	0·17	4·06	1·35	0·44	2·51	4·30	58	9·67
12-24	,,	,,	0·17	2·72	1·21	0·34	2·90	4·45	65	9·20
24-36	,,	,,	0·20	1·90	3·19	0·20	2·00	5·39	37	8·98
36-48	,,	,,	0·20	1·41	3·61	0·13	1·26	5·00	25	9·43
					After treatment (1931).					
0–12	0·10	Trace	Trace	0·24	4·06	0·29	0·21	4·56	5	7·05
12–24	0·12	,,	,,	0·28	3·75	0·15	0·44	4·36	10	7·50
24–36	0·07	,,	,,	0·57	4·05	0·37	0·38	4·80	8	8·80
36–48	Trace	,,	,,	0·79	3·66	0·30	0·85	4·81	17	9·30

The physical condition of the check plots has also undergone marked amelioration. Although the soil at the outset was extremely deflocculated and difficult to till, being very cloddy when ploughed and therefore unfavourable from an agronomic point of view, its physical condition has undergone pronounced improvement. During the past four or five years the tilth and permeability of these plots have become essentially normal.

Table III. *Distribution of water-soluble and exchangeable bases in the check plot of the Fresno experiment.*

Depth in in.	Milliequivalents per 100 gm. dry soil								Na as % of total	*p*H
	Water-soluble				Exchangeable					
	Ca	Mg	K	Na	Ca + Mg	K	Na	Total		
	Before leaching (1920).									
0–12	Trace	Trace	0·14	2·59	1·21	0·33	2·90	4·44	65	9·18
12–24	,,	,,	0·11	1·78	1·17	0·33	3·61	5·11	70	9·15
24–36	,,	,,	0·24	1·27	2·89	Trace	2·49	5·38	46	8·61
36–48	,,	,,	Trace	0·97	3·46	0·23	1·43	5·12	28	8·59
	After leaching (1931).									
0–12	0·06	Trace	Trace	0·56	4·66	0	0·30	4·96	6	8·07
12–24	0·04	,,	,,	0·69	4·44	0	1·20	5·64	21	8·70
24–36	Trace	,,	,,	1·15	4·35	0	1·54	5·89	26	9·03
36–48	,,	,,	,,	1·52	3·07	0	3·45	6·52	53	9·30

The data reported in Table III show that leaching without other treatment has removed a high percentage of the soluble salts and absorbed sodium from the upper 24 in. of the soil. It is also shown that the downward movement of the soluble salts has resulted in increases in both soluble and absorbed sodium and the *p*H of the subsoil (36–48 in.). The profound changes that have taken place in the base-exchange complex of this soil and the attendant amelioration of its physical properties have been produced largely through the agency of $CaCO_3$. This is shown by the determination of the insoluble carbonate of the soil

Table IV. *Insoluble CO_3 of Fresno soil as affected by different treatments (per cent.).*

Depth in in.	Gypsum plot		Sulphur plot		Check plot	
	Before treatment (1920)	After treatment (1931)	Before treatment (1921)	After treatment (1931)	Before leaching (1920)	After leaching (1931)
0–12	0·029	0·037	0·073	0	0·042	0·012
12–24	0·073	0·099	0·012	0	0·056	0·003

(see Table IV). The following equations offer a plausible explanation of the results:

$$\text{Na clay} + H_2O \rightleftarrows \text{H clay} + NaOH$$
$$\text{H clay} + CaCO_3 \rightleftarrows \text{Ca clay} + H_2CO_3$$
$$H_2CO_3 + 2NaOH \rightleftarrows 2NaHCO_3$$

or

$$\text{Na clay} + CaCO_3 \rightleftarrows \text{Ca clay} + Na_2CO_3.$$

Thus, it is possible to reclaim sodium soil by leaching without other treatment. The results of this experiment conflict somewhat with the conclusion of Gedroiz (9) and de 'Sigmond (23). Gedroiz holds that leaching an alkali sodium soil will prove to be injurious rather than beneficial owing to deflocculation and the formation of Na_2CO_3.

THE RECLAMATION OF NA-CA SALINE SOIL.

The preceding discussion on the evolution of alkali soils leads at once to the conclusion that the method of reclamation will be predetermined by the stage of evolution to which the soil has attained. As to whether or not the evolutionary process has passed beyond the salinisation stage will depend on the composition of the soluble salts that have accumulated in the soil. If soluble calcium is present to the extent of approximately 25 per cent. of the total soluble bases, the soil will be found to contain but little, if any, absorbed sodium. An alkali soil which conforms to these conditions must inevitably be in the salinisation stage, and its reclamation is merely a matter of removing the soluble salts. The alkali soils of the Imperial Valley, California, are of this kind. In certain parts of this valley the soil contains exceptionally high concentrations of soluble salts, but $CaCO_4$ is usually present in abundance.

A series of reclamation experiments were begun in the Imperial Valley in 1929 on a barren area of a deep clay loam alkali soil. The soil contained an extremely high concentration of soluble salts consisting mainly of sodium, calcium, and magnesium chlorides and sulphates. The soil was practically free from soluble carbonate. Certain plots were treated with gypsum, sulphur, or combinations of the two, both with and without barnyard manure. Three plots were left untreated as checks. After the above-named materials were applied, all of the plots, including the check plots, were flooded for a period of several weeks. Alfalfa, sown in October, 1930, germinated normally, and large yields have subsequently been obtained from all these plots alike. The reclamation has been fully as successful on the check plots as on the treated plots.

The data presented as Table V show that leaching has removed the greater part of the soluble salts. It is also shown that the base-exchange complex of the original soil of these plots contained very little absorbed sodium. Simple leaching, therefore, is all that is required to accomplish its reclamation. In order to leach the soil effectively the drainage conditions must, of course, be favourable. The soil of these experimental plots is underlain with a sandy layer of considerable thickness at a depth of about 8 ft., which facilitates drainage.

Table V. *Distribution of water-soluble and exchangeable bases in the check plot of the Imperial Valley experiment.*

	Millicquivalents per 100 gm. dry soil								
	Water-soluble				Exchangeable				
Depth in in.	Ca	Mg	K	Na	Ca + Mg	K	Na	Total	Na as % of total
				Before leaching (1929).					
0–12	26·0	14·0	2·4	50·8	13·70	0	0	13·70	0
12–24	4·7	4·3	1·6	14·7	14·55	0	0·2	14·75	1
24–36	2·8	2·1	1·3	9·0	11·30	0·04	1·8	13·14	13
36–48	1·8	1·9	1·0	7·5	17·92	0·11	1·7	19·73	9
				After leaching (1931).					
0–12	0·7	0·5	0·6	0·8	17·36	0·19	0·7	18·17	4
12–24	0·5	0·4	0·6	2·1	15·51	0·24	1·25	17·00	7
24–36	0·2	0·7	0·5	1·9	13·56	0·29	2·40	16·25	14
36–48	0·2	0·5	0·5	4·0	17·29	0·63	4·65	22·57	20

THE ABSORBED BASES OF ALKALI SOILS.

Referring again to Tables I, II, III and V, it will be noted that replaceable calcium and magnesium, both in the Fresno and the Imperial Valley soils, have been reported collectively rather than individually. This was done because none of the existing methods make possible the accurate determination of replaceable calcium and magnesium separately in such soils. The following discussion will explain why this is true.

Various students of base exchange have called attention to the fact that the determination of the several replaceable bases of soils necessitates giving due consideration to solubility effects. The determination is dependent upon two processes: first, the removal of the absorbed bases from the soil; second, the measurement of the extent to which solubility in contrast to ion exchange has influenced the analytical results. Now, it is certain that more or less decomposition and solution of various soil constituents take place under the conditions that are involved in the removal of the absorbed bases from soils in general.

Nevertheless, with the exception of water-soluble bases and $CaCO_3$, this fact is quite generally ignored by soil investigators.

Base exchange obviously denotes an exchange of bases, that is an interchange of cations between a solution and the insoluble constituents of the soil. In so far as cation exchange is concerned, all of the existing evidence with which the author is familiar indicates that the ion-exchange process is stoichiometric, which means that the cations of a salt solution, when brought into contact with the soil, undergo a change reciprocal to that of the soil; therefore the solution will lose some one or more of its cations in amounts equivalent to the amounts of cations that are replaced from the soil. On the other hand, whatever quantity of cations passes into solution by any process other than by ion exchange will not be accompanied by a corresponding absorption of cations from the solution. It follows, then, that the method employed for the determination of replaceable bases should provide a means of distinguishing between ion exchange and solution. The NH_4-absorption method, proposed originally by Kelley and Brown (14) and modified more recently by Chapman and Kelley (1), is designed to accomplish this end.

Solution, in contrast to ion exchange, is involved to some extent in the determination of absorbed bases with all soils. With alkali soils this factor may influence the results greatly. The preceding discussion on the origin of alkali soils shows that precipitated carbonates and silicates of calcium and magnesium may occur in such soils. Where these constituents are present there is no known method by which the actual amount of absorbed calcium or magnesium can be accurately determined.

The methods in common use for the determination of replaceable bases in soils involve, (*a*) extraction with a salt solution, usually some ammonium salt, (*b*) extraction with dilute acid, or (*c*) electrodialysis. All these methods bring about the decomposition or solution of carbonates and simple silicates, but neither carbonates nor simple silicates undergo ion exchange in the sense in which the term is commonly used in soil literature. The complications arising from the presence of carbonates are too well known to justify extended discussion. On the other hand, the fact that precipitated silicates may be present in alkali soil and that, when present, the determination of replaceable bases is made difficult thereby, is not generally recognised.

The essentials of the argument as to the occurrence of precipitated silicates in alkali soils have already been given. Their effect on the determination of the replaceable bases is due to the fact that they undergo marked decomposition when treated with ammonium salts, dilute acid, or when electrodialysed. When calcium silicate is leached with a solution of ammonium chloride or ammonium acetate, calcium passes into solution as the chloride or acetate, but ammonium ions are not absorbed from the solution to any great extent owing to the instability of ammonium silicate. Furthermore, the amount of SiO_2 that passes into the solution is not a reliable measure of the extent to which silicates of the soil have undergone decomposition, for the reason that under these conditions more or less colloidal SiO_2 is precipitated and absorbed by the soil.

Simple silicates cannot be responsible for the occurrence of absorbed sodium in alkali soils, since sodium silicate is soluble in water. As early as 1852 Way(24) called attention to the fact that the absorption of ammonia by soils cannot be due to simple silicates. He concluded that the absorption is due to alumino silicates. Soil scientists are now well agreed that the important aspects of base exchange in soils in general are due chiefly to the clays (alumino silicates) and humus constituents.

The accurate determination of the absorbed bases of alkali soils necessitates giving consideration also to the vaguely defined substances represented by the intermediate stages of the weathering process. It is highly probable that the weathering process which takes place in the soil itself is modified to some extent by the soluble salts which accumulate in alkali soils. Under these conditions practically all of the soluble products that are .formed within the soil by the weathering of minerals will remain in the soil. Since alkali soils probably contain minerals in every stage of alteration and decomposition, from the extremes of highly weathered soil on the one hand, to unaltered igneous minerals on the other, the interpretation of the base-exchange data is therefore complicated.

As a means of determining the total content of bases that are held in absorbed condition by the clay and humus of the soil, the following method has been devised. A sample of the soil is leached with neutral, normal, ammonium acetate as long as base of any kind is removed from the soil. The uncombined ammonium acetate, occluded by the sample, is removed by prolonged leaching with neutral methyl alcohol; then the absorbed NH_4 is determined by aeration. Sodium and potassium are determined in the ammonium acetate leachate of the soil, but calcium and magnesium are disregarded. The sodium and potassium data are corrected for water-soluble sodium and potassium. The absorbed NH_4, expressed as milliequivalents, is a measure of the total cation-exchange capacity of the soil. This quantity minus the sum of the absorbed Na and K equals exchangeable calcium and magnesium collectively. If the soil contains exchangeable H ions, it is necessary, of course, to determine the amount of the same and subtract this quantity from the absorbed NH_4 also.

DISCUSSION.

From the preceding, it is obvious that important advances have been made during recent years in our knowledge of alkali soils. Instead of alkali soil being merely arid or semi-arid soil in which an excess of soluble salts has accumulated, as Hilgard apparently believed, we now recognise a series of additional processes and transformations that are extremely important. Numerous investigators have contributed to this advancement, but soil scientists are especially indebted to the late Dr Gedroiz for his extraordinarily clear and comprehensive exposition of this subject. His contributions (4, 5, 6, 7, 8, 9, 10, 11) on the cation-exchange phenomena of soils and on the various relationships of cation exchange to the process of alkali soil formation, evolution, and reclamation constitute one of the most brilliant chapters in the history of science. De 'Sigmond (19, 20, 21, 22, 23), whose researches have been conducted entirely independently and for the most part without previous knowledge of Gedroiz' work, has also made important contributions. The investigations of the author and his associates have fully confirmed the principal conclusions of Gedroiz and de 'Sigmond.

American alkali soils are perhaps somewhat peculiar in that $CaCO_3$, calcium silicates and soluble calcium salts are especially abundant in them. This fact accounts in part for the special emphasis which we have given to the calcium constituents of alkali soils. In this paper the attempt has been made to show that the important properties of alkali soils are dependent not only on the soluble salts, as was emphasised by Hilgard, and the absorbed sodium, as has been emphasised by Gedroiz and de 'Sigmond, but also on the calcium minerals of the soil. The climatic conditions which bring about the accumulation of soluble sodium salts in the soil also tend to accentuate the accumulation of calcium compounds. If $CaCO_3$ be present in the soil, its influence is especially potent in that the evolutionary trends of the soil are profoundly affected by it. De 'Sigmond (23) has pointed out that the method of reclamation should be chosen on the basis of the evolutionary stage of the soil. The author holds that the method of reclamation should be based on the calcium constituents of the soil.

Broadly speaking, alkali soils may be divided into two groups on the basis of their content of absorbed sodium. The acquisition of absorbed sodium by the soil is a consequence of base exchange, occasioned by the accumulation of soluble salts therein. If Na_2CO_3 be present as a constituent of the soluble salts that have been transported to the soil, the formation of sodium-absorption compounds will be accompanied by the precipitation of the replaced calcium and magnesium as carbonates. Under these conditions, or if $CaCO_3$ be present in the soil for any other reason, the soil itself will contain a potential source of calcium by which the absorbed sodium can be replaced.

The important points to be determined, as a basis on which to project an intelligent programme of alkali soil reclamation, are: (*a*) the content and composition of the soluble salts, (*b*) the relative amount of absorbed sodium, (*c*) the abundance and general nature of the calcium minerals of the soil. To these should be added (*d*) knowledge as to the composition of the available irrigation water. Obviously, the calcium content of the irrigation water may be utilised as an important source of soluble calcium. Since reclamation must involve the removal of the excess of soluble salts and the replacement of absorbed sodium by calcium, leaching conditions are essential to successful reclamation.

Whether or not the application of a soluble calcium salt will be necessary in a given case, will depend first of all on the content of absorbed sodium. In general it may be said that the reclamation of alkali soils which contain considerable water-soluble calcium will not be aided by the application of a calcium salt. Such soils do not contain important amounts of absorbed sodium and they are likely to be reasonably well flocculated. Their reclamation is merely a matter of leaching out the excess of soluble salts.

Alkali soils which contain relatively much absorbed sodium may or may not require the application of a soluble calcium salt. If sufficient amounts of $CaCO_3$ be present, means may be employed by which its solubility will be so increased as effectively to provide the necessary soluble calcium. As was pointed out by Kelley and Arany (13), the application of sulphur, iron sulphate, alum or any acid substance will accomplish this objective. On the other hand, if $CaCO_3$ be absent, the necessary calcium must be obtained from an external source.

As de 'Sigmond (23) has shown, the application of lime is an effective means of reclaiming the degraded alkali soils of Hungary. Upon applying lime, $CaCO_3$ probably reacts with the base unsaturated-exchange complex of soil as follows:

$$\text{H-absorption complex} + CaCO_3 \rightleftarrows \text{Ca-absorption complex} + Ca(HCO_3)_2.$$

The $Ca(HCO_3)_2$ thus formed then replaces absorbed sodium as follows:

$$Ca(HCO_3)_2 + \text{Na-absorption complex} \rightleftarrows \text{Ca-absorption complex} + NaHCO_3.$$

Thus the base-unsaturated constituents and the Na-absorption compounds, both of which occur in degraded alkali soils, are converted into calcium compounds by $CaCO_3$. Were it possible to effect a thorough distribution of the applied $CaCO_3$ throughout the soil profile, the rate of the reclamation of degraded soil would be relatively rapid, for base-unsaturated soil reacts with $CaCO_3$ actively. However, there seems to be no practical method of doing this. The reclamation of the subsoil horizons is dependent on the leaching downward of $Ca(HCO_3)_2$, and this is a relatively slow process at best. It may be extremely slow with heavy types of degraded soil.

De 'Sigmond ((23), p. 5) has also suggested the importance of $CaCO_3$ in other types of alkali soil as is shown by the following:

> For practical purposes we may group alkali soils according to their salt and lime content into soils rich or poor in alkali, and soils containing, or free from, calcium carbonate. Combining the two groups, we have the following four soil types:
>
> (i) Soils rich in alkali and $CaCO_3$.
> (ii) Soils poor in alkali, but with considerable $CaCO_3$.
> (iii) Soils rich in alkali, but free of $CaCO_3$.
> (iv) Soils poor in alkali, and free of $CaCO_3$.
>
> These characteristics are easily recognised in the field, and knowing them, we can then form an idea of the most suitable measures for reclamation. But in order to understand the effect of the measures, and to employ them successfully, we must understand the nature of the changes they produce in the dynamics of the soil.

The fact that $CaCO_3$ has a low solubility in alkaline solutions prompted de 'Sigmond (23) and Gedroiz (9) to conclude that $CaCO_3$ would be ineffective in the reclamation of alkali soils that contain Na_2CO_3. However, they overlooked the fact that leaching may so reduce the content of Na_2CO_3 and lower the *p*H of the soil as to permit $CaCO_3$ to take part in the reactions. That this is true is attested by the results on the check plots of the Fresno experiments.

As stated already, any agency which brings about an increase in the solubility of the calcium minerals of the soil will promote the reclamation of alkalinised soil. In this connection CO_2 must be considered. The beneficial effect of organic manures is probably due largely to the fact that CO_2 is formed in their decomposition. Hilgard pointed out that alfalfa, once established on black alkali soil, is able to continue growth under conditions which are prohibitive of the growth of young alfalfa seedlings. The reason for this fact is not that old alfalfa plants are especially tolerant of high concentrations of Na_2CO_3, but rather that the extensive root system of the established plants creates a more favourable condition in the soil through the exudation of CO_2. By this means Na_2CO_3 is converted into $NaHCO_3$. The consequent lowering of the *p*H of the soil permits the solution of $CaCO_3$. Thus the alfalfa plant is able through this means to secure its required calcium.

Advantage may be taken of the principles just discussed in connection with the reclamation of alkalinised soil. By growing alkali-resistant crops (*e.g. Melilotus alba*) as green manure, we have been able to promote the reclamation process substantially. In the decay of the green manure CO_2 is formed which reduces the OH-ion concentration of the soil and in turn brings about the solution of $CaCO_3$. If leached occasionally, $NaHCO_3$ that is formed by these reactions will be carried away and $Ca(HCO_3)_2$ will be caused to penetrate into the subsoil horizons and thus to ameliorate the same.

In this connection it is of interest to point out that $CaCO_3$ has played an important part in the reclamation of the gypsum plots of the Fresno experiments. Samples drawn in 1921 after the termination of the leaching process showed that practically all of the applied gypsum had been converted into $CaCO_3$ or absorbed calcium. At that time the soil still contained relatively much absorbed sodium. Subsequently, $CaCO_3$ has gradually reacted with the Na clay of this plot until practically all of the absorbed sodium has finally been replaced by calcium. From the standpoint of alkali soil reclamation, we may say, therefore, that the relatively insoluble calcium minerals of the soil are very important.

The content of clay is also an important consideration. De 'Sigmond (23) has pointed out that leaching, as a method of reclamation, has proved unsuccessful in Hungary owing to the extremely impervious nature of the soil and subsoil. With heavy types of alkaline Na-clay soils, it is improbable that simple leaching can ever be made effective. In such cases some flocculating agent should be applied, such as gypsum, soluble iron, or aluminium salts. At best the reclamation of heavy clay types of alkali soil is extremely difficult.

SUMMARY.

1. The formation of alkali soils is primarily a question of soluble salt accumulation. Those processes which bring about the accumulation of soluble salts in soils also tend to cause the accumulation of $CaCO_3$. Under certain conditions simple calcium silicates may also be precipi-

tated in alkali soils. Hilgard's researches were concerned chiefly with the soluble salts. On the other hand, more recent investigators have emphasised the base-exchange aspects of the subject. Sodium salts tend to react with the clay and humus constituents of the soil, converting them into Na-absorption compounds. These components produce extremely adverse conditions in the soil.

2. Under certain conditions alkali soils tend to pass through four evolutionary stages, namely, salinisation, alkalinisation, desalinisation, and degradation. As to whether or not an alkali soil will pass beyond the salinisation stage, depends on the composition of the soluble salts that accumulate in it. Where sodium salts predominate, more or less alkalinisation of the exchange complex has taken place. However, this is not true where soluble calcium is relatively abundant.

3. Desalinisation (by leaching, whether natural or artificial) of alkalinised soil is usually accompanied by the formation of Na_2CO_3 and by pronounced deflocculation. If $CaCO_3$ be present, the formation of Na_2CO_3 is accompanied by the replacement of absorbed sodium by calcium. Under these conditions the degradation stage will not be attained. If $CaCO_3$ be absent, base-unsaturated constituents arise under leaching conditions, and more or less of the inorganic-exchange complex becomes decomposed into simple oxides.

4. The evolutionary stage of the soil predetermines, in considerable measure, what reclamation process should be employed. If the soil has not passed beyond the salinisation stage, simple leaching will effect satisfactory reclamation. This conclusion has been verified by plot experiments in the Imperial Valley, California. If the exchange complex has become alkalinised to any important extent, the absorbed sodium must be replaced by calcium. This can be accomplished either by treating the soil with a soluble calcium salt and leaching, or by reducing the OH-ion concentration of the soil to a point where $CaCO_3$, if present, will react with the Na-absorption compounds.

5. Experiments near Fresno, California, have demonstrated the effectiveness of gypsum and sulphur as treatments for strongly alkaline sodium soil. It has been found also that prolonged leaching will accomplish the reclamation of this soil. Upon leaching, $CaCO_3$ gradually reacts with the exchange complex of this soil, converting the same into calcium absorption compounds. The same result can be more quickly produced by applying sulphur, iron sulphate, alum, or other acid materials.

6. Degraded alkali soil can be reclaimed, as de 'Sigmond has shown, by applying lime.

7. Alkali soils may contain carbonates and simple silicates of calcium and magnesium. This fact makes difficult the determination of the absorbed calcium and magnesium.

8. In addition to the soluble salts, which Hilgard emphasised especially, and the base-exchange constituents, which Gedroiz, de 'Sigmond, and others have emphasised, the author wishes to direct attention to the calcium constituents of alkali soils. The amount and kind of calcium minerals in the soil predetermine both its evolutionary trend and the method of reclamation that should be employed.

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NUTRITIVE VALUE OF PASTURE.

X. THE UTILISATION OF YOUNG GRASS BY SWINE.

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Introduction.

Although it has been recognised for many years that breeding pigs benefit greatly in health and general condition by being kept out-of-doors with a free run on grass, it is only during the last two decades that any attempt on more than a small scale has been made to extend this practice to pig-keeping in general. During recent years, however, the system of open-air pig-keeping, involving the keeping of pigs on grass or the feeding of suitable green crops on arable land, has gained many adherents among commercial pig-feeders and has become a recognised feature of swine husbandry in this country.

In order that the rationing of pigs under the open-air system should be capable of being controlled in as satisfactory a manner as under the indoor-housing system, it is desirable that information should be available as to (1) the amount of grass (or green crop) that can be consumed per day by pigs of different live-weights, and (2) the nutritive value of grass (or green crop) when consumed by pigs and the amount of meal that is capable of being replaced by 1 lb. of grass (or green crop). On both these matters only meagre information is available.

Tod (1) states that the quantity of grass consumed by pigs is not very large, and even when there is abundance and the pigs are given comparatively small quantities of concentrated food, it is probable that a sow does not consume more than 12–15 lb. per day. Stewart (W. A.) (2), on the basis of observations with regard to green or root crops generally, concludes that a sow will account for about 20 lb. of green food per day and that a 6-months-old pig will consume 12–14 lb.

It is the purpose of the present communication to bring forward the results of digestion trials designed to discover the degree to which pigs are able to digest and utilise young grass. If grass is to be fed as an essential energy- and protein-contributing component of a pig's diet (and not merely in small amount with a view to supplying certain accessory factors), then it should be utilised in its young stages of growth, since there can be no question whatsoever as to the low feeding value for swine of mature and partially-lignified herbage. Young grass has been shown to constitute, for ruminants, an excellent source of starch equivalent and digestible protein(3); it by no means follows, however, as will be shown in this communication, that such herbage has a value for pigs equal to, or even approximating to, that which it has in the nutrition of ruminant animals.

PLAN OF DIGESTION TRIALS.

Two Large White hogs, weighing 157 and 150 lb. respectively at the beginning of the experiment, were employed in the digestion trials. In the first trial, the digestibility of a basal ration composed of equal parts by weight of maize meal and coarse middlings was determined. In the following two periods, the amount of basal food was cut down to an appropriate level and definite weights of the grass to be tested were added. The details of the rations as fed to the pigs are recorded in Table I, although for the amounts of grass actually consumed by the animals, the tables in the appendix should be consulted.

Table I. *Details of digestion rations.*

	Period 1		Period 2		Period 3	
	Amount per day gm.	Dry matter per day gm.	Amount per day gm.	Dry matter per day gm.	Amount per day gm.	Dry matter per day gm.
Maize meal	1100	971·5	750	664·2	750	664·3
Coarse middlings	1100	949·0	750	652·9	750	656·3
Pasture herbage	—	—	2000	570·6	2000	502·0

The mixture of maize meal and middlings was fed in the soaked condition in all three periods. During periods 2 and 3, the metabolism crate (see reference (4)) was so modified as to enable the animals to have continuous access throughout the day to the trough containing the grass, since the necessity of masticating the herbage before swallowing rendered the consumption of this component of the diet a slow procedure compared with the consumption of the meal. Opportunity for drinking water was afforded at frequent intervals. The grass remaining in the troughs at 5 p.m. was removed and retained for dry matter determinations, so that the mean daily amounts of grass residues, in terms of dry matter, could be ascertained. At this stage the soaked meal was fed and on all occasions was consumed readily and completely.

Although the pigs had never received grass in any form prior to this experiment, they displayed from the outset considerable eagerness for this portion of the ration. It will be noted from the tables in the appendix that pig 1 in both periods consumed almost the whole of its bulky grass allowance, whereas pig 2 left distinctly larger amounts of the grass uneaten. During both periods, the animals seemed perfectly contented and healthy. The dung was of satisfactory consistency, being slightly softer than when the pigs were on meal only. It was greenish in colour, and the presence in it of unassimilated residues from the grass was easily detected.

The samples of grass for feeding to the pigs were secured from the light-land pasture on which the series of investigations into the yield, composition and nutritive value of pasturage under different systems of cutting has been carried out (5). Very short, leafy grass was used in period 2, the herbage having been obtained by mowing a number of the sub-plots in April, 1933, and allowing the grass, before cutting again for the purposes of the trial, to grow unchecked during a period varying from one to two weeks. It was no more than 1 to 2½ in. in height and contained, on the basis of soil-free dry matter, 26·04 per cent. of crude protein and 16·73 per cent. of crude fibre.

Table II. *Composition of feeding stuffs (dry matter basis).*

	Maize meal	Coarse middlings	Pasture herbage (period 2)		Pasture herbage (period 3)	
			As cut	Calculated* to soil-free basis	As cut	Calculated* to soil-free basis
	%	%	%	%	%	%
Crude protein	10·71	18·40	24·32	26·04†	16·14	16·76‡
Ether extract	5·82	5·23	3·57	3·82	3·10	3·22
N-free extractives	79·35	64·59	41·78	44·73	50·68	52·62
Crude fibre	2·35	7·54	15·62	16·73	18·70	19·42
Ash	1·77	4·24	14·71	8·68	11·38	7·98

* See reference (5).
† Including 22·42 per cent. of true protein.
‡ Including 13·36 per cent. of true protein.

Somewhat longer and older grass was used in period 3. The area from which this grass had been cut had last been mown in December, 1932, for the purpose of winter grass-feeding trials. Since that date it had been permitted to grow unchecked, and at the beginning of period 3 (April 29, 1933) the height of the grass varied from 2 to 5 in. Perennial rye grass was the most prominent species in the area, and patches of cocksfoot were also numerous. By the end of the period in mid-May, the perennial rye grass was rather more than 6 in. high, while some rye grass stems, which appeared during the course of the digestion trial, had run up to about 10 in.

The composition, on the basis of dry matter, of the maize meal, middlings and two pasture grass composites is recorded in Table II. The data for the pasture samples are also given on the soil-free basis (see reference (5)). The mean moisture content of the different foods may be calculated from the data in Table I.

RESULTS OF DIGESTION TRIALS.

In Table III are summarised the mean digestion coefficients for the basal ration of maize meal and middlings and for the two grades of pasture herbage. For the comprehensive details of the results of the digestion trials, the reader should consult the tables in the appendix.

Table III. *Summary of digestion coefficients (mean for two pigs).*

	Period 1 Basal ration (equal parts of maize meal and coarse middlings)	Period 2 Pasture grass (containing 26·0 % crude protein and 16·7 % crude fibre on D.M. basis)	Period 3 Pasture grass (containing 16·8 % crude protein and 19·4 % crude fibre on D.M. basis)
	%	%	%
Crude protein	84·1	66·6	55·0
Ether extract	80·7	—	—
N-free extractives	88·6	71·2	68·9
Crude fibre	30·4	56·9	55·4
Total organic matter	84·6	61·9	60·3

Reference to the tables in the appendix shows that the agreement between the digestion coefficients for the two pigs in period 1 (basal ration of maize meal and middlings) was very satisfactory, the values in the case of the organic matter of the ration, for example, being 84·12 and 84·98 per cent. for pig 1 and pig 2 respectively. The agreement in period 2, when the very young grass formed part of the ration, was not so good, pig 2 digesting the N-free extractives and fibre of the grass more efficiently than did pig 1, although in respect of crude protein digestibility, the difference was only very slight. The digestion coefficients of the total organic matter of the grass were 58·9 per cent. (pig 1) and 64·8 per cent. (pig 2), with a mean value of 61·9 per cent.

This difference in the utilisation of the grass by the two experimental animals may have been due to the fact that pig 1 consumed a larger grass ration than pig 2, the additional weight of bulky food possibly having led to a slight depression of the digestibility of the ration as a whole. Further, pig 1 ate its grass ration quickly, with but hasty attempts at mastication, whereas pig 2 ate the herbage slowly and masticated this portion of its ration with deliberation and efficiency. During period 3, when the older grass was fed, the agreement between the grass digestion coefficients for the two pigs was much closer than in period 2, the values for the organic matter of the grass being 59·4 and 61·1 per cent. for pig 1 and pig 2 respectively.

The data in Table III show very clearly that the Large White hogs (which averaged about 195 lb. live-weight during the carrying out of the grass periods of feeding) were unable, with the exception of the fibrous component, to digest the constituents of even young grass with anything like the same degree of efficiency as they displayed in the digestion of the basal ration of middlings and maize meal. The lower digestibility of the grass as compared with the meal is brought out by the digestion coefficients of the protein, oil and carbohydrate in the rations. In the case of the crude oil fraction, it would appear that the grass not only failed to supply any digestible oil, but actually caused a depression of the digestibility of the oil in the basal ration of meal. This, however, may be merely an apparent effect, since it may equally well be explained by assuming an increase in the output of "metabolic" ether-soluble material in the faeces as a result of rendering the food less easy of digestion and assimilation consequent on the inclusion of the bulky grass in the ration. In contrast with the foregoing observations, it is of interest to find that the fibre of the grass was distinctly more digestible than the fibre in the concentrated meal. The relative values of the pasturage and mixed meal are best brought out by the data for the digestion coefficients of the total organic matter; the pigs were able to digest about 85 per cent. of the organic matter of the meal, and only 60–62 per cent. of that contained in the grass.

The constituents of the older grass used in period 3 were not, with one notable exception, markedly less digestible than those of the very young grass of period 2. Only in the crude protein was there any notable difference, the protein in the older grass, besides being smaller in amount (16·8 per cent. as against 26·0 per cent. on the dry matter basis), displaying also a significantly less digestible character (55·0 per cent. as against 66·6 per cent.).

In Table IV are given data showing the amounts of digestible nutrients available to swine per 100 lb. of the mixed meal ration and per

100 lb. of the two grades of pasturage. The figures in every case relate to 100 lb. of the dry matter in the foods.

Table IV. *Digestible nutrients available to swine per* 100 *lb. of food (dry matter basis).*

	Period 1 Basal ration (equal parts of maize meal and middlings) lb.	Period 2 Pasture grass (containing 26·0 % crude protein and 16·7 % crude fibre on D.M. basis) lb.	Period 3 Pasture grass (containing 16·8 % crude protein and 19·4 % crude fibre on D.M. basis) lb.
Dig. protein	12·24	17 34	9·22
Dig. ether extract	4·46	—	—
Dig. N-free extractives	63·77	31·85	36·26
Dig. fibre	1·51	9·52	10·76
Dig. organic matter	81·98	58·71	56·24

The data in Table IV show that 100 lb. of the dry matter in the meal ration of equal parts of maize meal and middlings supplied the pigs with as much as 82 lb. of digestible organic matter (including 12·2 lb. of digestible protein), whereas the very young grass fed in period 2 supplied, per 100 lb. of dry matter, only 58·7 lb. (containing 17·3 lb. of digestible protein) and the somewhat older grass used in period 3, 56·2 lb. of digestible organic matter (including 9·2 lb. of digestible protein). Averaging the results of periods 2 and 3, it may be concluded that 100 lb. of the dry matter in young grass furnishes 57·5 lb. of digestible organic matter for purposes of maintenance and production in pigs. From the foregoing results, and assuming a moisture content of 12 and 80 per cent. respectively in the meal and grass, it may be shown that, from the standpoint of supply of digestible organic matter, 1 lb. of the mixed meal is equivalent to 6·3 lb. of fresh young pasture herbage.

The conclusion may be drawn, therefore, that the consumption of 6–7 lb. of such grass should enable the saving of 1 lb. meal to be effected. But if Stewart's estimate be taken as correct, namely, that a 6-months-old pig will not consume more than 12–14 lb. of green food per day (2), it is clear that such an allowance of grass, *even in its young and most highly digestible condition*, would not be equivalent to more than about 2 lb. of meal. If satisfactory rates of live-weight increase are to be realised in the case of growing pigs on grass, attention must be directed to ensuring that the animals are consuming, besides the grass, an adequate ration of concentrated meal. Indeed, when grass constitutes a substantial proportion of the dietary of pigs, it is not feasible to anticipate such rapid increase of live-weight as is possible when the ration is composed wholly of such concentrated and easily-assimilated foods as barley meal, maize meal, middlings, fish meal, etc. Not only is the dry matter of the grass much less digestible than that of the meal, but the herbage is a bulky food from the standpoint of swine nutrition and must tend to restrict the weight of food, in terms of dry matter, which the animal is capable of consuming per day. Further, as is indicated by the results of the present experiment, the herbage in the diet may actually depress the digestibility of the meal fraction, particularly that of the oil constituent, a depression which might become very significant if the grass allowance were increased. In the present trials, where the grass formed, on the dry matter basis, 27–30 per cent. of the total ration of pig 1 and 20–25 per cent. in the case of pig 2 (see tables in appendix), the animals displayed a mean daily live-weight gain of about $\frac{2}{3}$ lb., compared with a corresponding mean daily gain of about $1\frac{1}{2}$ lb. on the ration composed wholly of maize meal and middlings.

It should further be borne in mind that when growing pigs are allowed freedom for grazing, a very definite amount of energy will be expended in roaming about and in biting off and masticating the grass. The energy thus used up per day in muscular activity will be significantly greater than that expended under good conditions of management with sty-fed pigs. For this reason, the *net* contribution of the grazed herbage towards the maintenance and productive processes in the animal is probably significantly smaller than is represented by the conclusion drawn from the results of the present digestion trials, namely, that 6–7 lb. of young grass is equivalent to 1 lb. of meal.

Presumably with grass in a more advanced stage of maturity, the value in the nutrition of swine would be still lower than that arrived at for young herbage in these trials, and more than 6–7 lb. would be required to replace 1 lb. of ordinary pig meal. In such circumstances, it is probable that Stewart's estimate may be taken as reliable, namely, that "so far as data on the subject are available, it would appear that pigs digest only about 40 per cent. of the green food that they consume, as against 80–90 per cent. of barley meal and other suitable concentrated foods. 8–10 lb. of grass is roughly equivalent to 1 lb. of meal. In spite of this, it is sound and economical to feed green food; but it is doubtful whether it is ever sound to allow pigs to depend entirely on green food as their sole diet." (2).

It may be concluded, therefore, that when intensive progress is looked for in growing or fattening pigs, grass, even in its young growth, should not form more than a small proportion of the ration; the feeder should rely mainly on the usual concentrated meal rations. For in-pig sows that are being permitted unrestricted grazing, the herbage so secured (say 12–15 lb. per day(1)) should be looked on as furnishing the equivalent of no more than about 2 lb. of concentrated meal in the case of young grass, and about 1½ lb. in the case of more mature grass. Indeed, in view of the energy expended by the sows in grazing and moving about, it is extremely probable that the *net* value of the grass ration is actually smaller than is represented by these figures. In support of this statement, it may be noted that under conditions of commercial pig-breeding, the writers have found that whereas 10–15 in-pig sows will keep about 4 acres of good grass closely-grazed all the year round, the shortest of grass being readily bitten off, yet it has always been found necessary, even when grass is abundant, to feed at least 4 lb. of meal per head to maintain the animals in good condition.

It has also been observed that sows suckling litters exhibit a fondness for grazing, even when they are consuming as much as 14 lb. of meal daily. All classes of pigs, from 6-weeks-old animals to full-grown sows, have been found to eat mown-grass very readily, whether this consists of the shortest of lawn clippings, or herbage secured by mowing at monthly intervals. Suckling sows, receiving their customary rations of meal, will readily consume in addition an allowance of 5 lb. of such grass. To growing pigs, however, only small allowances have been fed, and then only when the animals have eaten their full allowance of meal.

COMPARATIVE UTILISATION OF YOUNG GRASS BY SHEEP AND SWINE.

It will readily be concluded, from the foregoing account, that pigs are unable to utilise the constituents of young grass with the degree of efficiency manifested by ruminant animals. This conclusion is emphasised by the data in Table V, in which the digestion coefficients obtained with swine in the present trials are compared with corresponding figures from sheep digestion trials on grass of similar nature and composition.

The all-round superiority of young grass as a source of digestible nutrients for sheep as compared with pigs is clearly brought out by the data in Table V. It will be noted that 100 lb. of the dry matter in such herbage furnishes the ruminant animal with 75·2 lb. of digestible organic matter, as against 58·7 lb. in the case of the pig. The explanation of this difference is fairly clear. In the case of the sheep, the bacterial digestion of the fibrous cell walls takes place in the rumen, and the nutrients, such as protein and carbohydrate, are thus liberated from the cells and

Table V. *Utilisation of young grass by sheep and swine**.

	Sheep (5) %	Swine (present trials) %
Digestion coefficient of crude protein	85·4	66·6
Digestion coefficient of ether extract	60·0	—
Digestion coefficient of N-free extractives	87·4	71·2
Digestion coefficient of crude fibre	79·2	56·9
Digestion coefficient of organic matter	83·6	61·9
On basis of dry matter:		
Digestible protein	22·5	17·3
Digestible organic matter	75·2	58·7

* The young herbage, in the sheep trial, contained, on the basis of dry matter, 26·37 per cent. of crude protein and 13·46 per cent. of crude fibre. The herbage fed to the pigs in the present trial contained 26·04 and 16·73 per cent. respectively of these constituents.

made easily accessible to enzymatic activity in the subsequent stages of digestion. With the pig, however, despite the fact that the fibre of the grass is digested to the extent of about 57 per cent., the bacterial action on this constituent takes place in the caecum and colon; *i.e. after* the food has been subjected to the normal digestive activity of the enzymes. For this reason, the grass has not undergone the preparatory changes which are characteristic of ruminant digestion, and the extent of digestion of protein and carbohydrate by the enzymes is restricted by the protective influence of the unbroken-down cell-wall material.

SUMMARY.

In this communication are brought forward the results of digestion trials designed to discover the degree to which pigs are able to digest and utilise young grass. Three digestion trials have been carried out. In the first trial, the digestibility of a basal ration composed of equal parts of maize meal and coarse middlings was determined. In the following two periods, the amount of basal food was cut down to an appropriate level and definite weights of the grass to be tested were added. In period 2, very short, leafy grass, containing, on the basis of dry matter, 26·04 per cent. of crude protein and 16·73 per cent. of crude fibre, was used, whilst somewhat older grass, containing 16·76 and 19·42 per cent. crude protein and fibre respectively, was fed in the third period.

It was found that the Large White hogs, which averaged about 195 lb. live-weight during the carrying out of the grass periods of feeding, were unable, with the exception of the fibrous component, to digest the constituents of even young grass with anything like the same degree of efficiency as they displayed in the digestion of the basal ration of middlings and maize meal. The constituents of the older grass, with the

exception of the crude protein, were not markedly less digestible than those of the very young grass. The relative values of the pasturage and mixed meal are best brought out by the data for the digestion coefficients of the total organic matter; the pigs were able to digest about 85 per cent. of the organic matter of the meal, and only 60–62 per cent. of that contained in the grass.

A consideration of the results leads to the conclusion that the consumption of 6–7 lb. of such grass as was used in these trials should enable the saving of 1 lb. of meal to be effected. If it be assumed that a 6-months-old pig will not consume more than 12–14 lb. of green food per day, it is clear that such an allowance of grass, even in its young and most highly digestible condition, will not be equivalent to more than about 2 lb. of meal. If satisfactory rates of live-weight increase are to be realised in the case of growing pigs on grass, attention must be directed to ensuring that the animals are consuming, besides the grass, an adequate ration of concentrated meal. Indeed, when grass constitutes a substantial proportion of the dietary of pigs, it is not feasible to anticipate such rapid increase in live-weight as is possible when the ration is composed wholly of the usual mixture of concentrated meal. Not only is the grass much less digestible than the meal, but the herbage is a bulky food from the standpoint of swine nutrition and must tend to restrict the weight of food, in terms of dry matter, which the animal is capable of consuming per day.

It should further be borne in mind that when growing pigs are allowed freedom for grazing, a very definite amount of energy will be expended in roaming about and in biting off and masticating the grass. For this reason, the *net* contribution of the grazed herbage towards maintenance and production in the animal is probably significantly smaller than is represented by the conclusion drawn from the results of these trials, namely, that 6–7 lb. of young grass is equivalent to 1 lb. of meal.

Presumably with grass in a more advanced stage of maturity, the value would be still lower; in such circumstances, it is probable that Stewart's estimate may be taken as reliable and that 8–10 lb. of grass is roughly equivalent to 1 lb. of meal.

Data are brought forward illustrating the all-round superiority of young grass as a source of digestible nutrients for sheep (and other ruminants) as compared with pigs.

The writers take this opportunity of thanking their colleague, Dr R. E. Evans, for assistance in the carrying out of this investigation.

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APPENDIX

I. *Summary of nitrogen balances.*

Period	Pig	N consumed per day gm.	N voided per day Faeces gm.	 Urine gm.	 Total gm.	Mean daily nitrogen balance gm.
1. Basal food	1	44·59	7·70	22·54	30·24	+14·35
	2	44·59	6·46	22·73	29·19	+15·40
2. Including very young grass	1	52·32	12·52	22·48	35·00	+17·32
	2	48·20	10·31	21·71	32·02	+16·18
3. Including somewhat older grass	1	43·56	11·17	19·79	30·96	+12·60
	2	39·16	8·19	19·58	27·77	+11·39

II. *Digestion tables.*

	Pig 1							Pig 2						
	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.
Period 1. Basal ration														
Maize meal	971·50	954·31	104·05	56·54	770·89	22·83	17·19	971·50	954·31	104·05	56·54	770·89	22·83	17·19
Middlings	949·00	908·76	174·62	49·63	612·96	71·55	40·24	949·00	908·76	174·62	49·63	612·96	71·55	40·24
Total consumption	1920·50	1863·07	278·67	106·17	1383·85	94·38	57·43	1920·50	1863·07	278·67	106·17	1383·85	94·38	57·43
Voided	339·70	295·89	48·14	20·49	159·38	67·88	43·81	318·36	279·85	40·36	20·45	155·51	63·53	38·51
Digested	1580·80	1567·18	230·53	85·68	1224·47	26·50	13·62	1602·14	1583·22	238·31	85·72	1228·34	30·85	18·92
Digestion coefficients (%)	82·31	84·12	82·73	80·70	88·48	28·08	23·72	83·42	84·98	85·52	80·74	88·76	32·69	32·94
Period 2. Including very young grass														
Maize meal	664·20	652·45	71·14	38·66	527·04	15·61	11·75	664·20	652·45	71·14	38·66	527·04	15·61	11·75
Middlings	652·90	625·22	120·13	34·15	421·71	49·23	27·68	652·90	625·22	120·13	34·15	421·71	49·23	27·68
Grass	558·20	476·09	135·75	19·93	233·22	87·19	82·11	452·00	385·51	109·93	16·14	188·84	70·60	66·49
Total consumption	1875·30	1753·76	327·02	92·74	1181·97	152·03	121·54	1769·10	1663·18	301·20	88·95	1137·59	135·44	105·92
Total voided	486·56	398·78	78·24	45·93	187·76	86·85	87·78	394·75	327·58	64·44	39·18	152·00	71·96	67·17
Total digested	1388·74	1354·98	248·78	46·81	994·21	65·18	33·76	1374·35	1335·60	236·76	49·77	985·59	63·48	38·75
Digested from basal food	1084·01	1074·66	158·24	58·76	839·45	18·21	9·35	1098·66	1085·67	163·57	58·79	842·11	21·20	12·99
Digested from grass	304·73	280·32	90·54	—	154·76	46·97	24·41	275·69	249·93	73·19	—	143·48	42·28	25·76
Digestion coefficients of grass (%)	54·59	58·88	66·70	—	66·36	53·87	29·73	60·99	64·83	66·58	—	75·98	59·88	38·74
Period 3. Including somewhat older grass														
Maize meal	664·30	652·54	71·15	38·66	527·12	15·61	11·76	664·30	652·54	71·15	38·66	527·12	15·61	11·76
Middlings	656·30	628·47	120·76	34·32	423·90	49·49	27·83	656·30	628·47	120·76	34·32	423·90	49·49	27·83
Grass	497·90	441·24	80·36	15·43	252·34	93·11	56·66	327·30	290·06	52·83	10·15	165·88	61·20	37·24
Total consumption	1818·50	1722·25	272·27	88·41	1203·36	158·21	96·25	1647·90	1571·07	244·74	83·13	1116·90	126·30	76·83
Total voided	463·20	382·88	69·81	31·95	191·03	90·09	80·32	363·37	305·23	51·19	27·45	156·56	70·03	58·14
Total digested	1355·30	1339·37	202·46	56·46	1012·33	68·12	15·93	1284·53	1265·84	193·55	55·68	960·34	56·27	18·69
Digested from basal food	1086·79	1077·40	158·77	58·89	841·46	18·28	9·39	1101·49	1088·45	164·12	58·92	844·13	21·28	13·04
Digested from grass	268·51	261·97	43·69	—	170·87	49·84	6·54	183·04	177·39	29·43	—	116·21	34·99	5·65
Digestion coefficients of grass (%)	53·93	59·37	54·37	—	67·71	53·53	11·54	55·92	61·15	55·71	—	70·06	57·17	15·17

NOTE. The care of the experimental animals was in the hands of Messrs V. Thurlbourn and C. Bendall.

THE EFFECTS OF RAINFALL AND TEMPERATURE ON PERCOLATION THROUGH DRAIN GAUGES.

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(With Eight Text-figures.)

INTRODUCTION.

THE complexity of the physical factors controlling the quantity of water discharged by a drain gauge has been long recognised at Rothamsted. The three gauges containing respectively 20, 40 and 60 in. of soil have been installed since 1870. For the present study the 55 years, 1878–1932, have been taken. The object has been to ascertain to what extent the drainage in a month can be predicted from the recorded rainfall and temperature of the same month. It will appear that from 74 to 98 per cent. of the observed variance can be thus predicted, the precision of the predictions being greatest in the winter, doubtless because the gauges are most nearly saturated at this time of the year.

The enquiry would have been a relatively simple one but for the occurrence of slow secular changes, probably affecting the physical condition of the soil in the gauges. The existence of such changes was pointed out by Russell(2) in 1907. Russell especially noted the fact that these changes were not identical in the three gauges and that in this matter, as in some others, the three gauges, though in general remarkably similar in their discharge, showed notable individuality. In the present enquiry, therefore, allowance has been made for a steady change in the constants of the prediction formula. The formulae thus show (i) the expected percolation for each gauge under standard conditions for each month of the year, and the average rate of change of this quantity over the 55 years, (ii) the increment to be expected for each additional inch of rain in each month, and its average rate of change, and, finally, (iii) the difference to be expected for each additional degree of temperature, in the mean temperature of the month, and the average rate of secular change of this quantity.

In addition to these formulae, the residuals or deviations from the predicted values have been calculated and filed at Rothamsted. These, it is hoped, will form the basis of further enquiries, suggested by the many unexpected features presented by the data. In the present paper they have been used only to construct the series of percolation values, shown by Fig. 1 *a*, for the eleven periods of 5 years each, after correction for variation of temperature and rainfall, by which the absolute and relative values of the change in percolatability of the different gauges may be represented.

METHOD OF INVESTIGATION.

In considering the meteorological factors which may be expected to influence the amount of water percolating through the depth of soil in the drain gauge, attention is naturally directed towards the rainfall and the prevailing temperature. The object of the present enquiry is to ascertain to what extent the drainage recorded in a given calendar month can be expressed in terms of the rainfall and temperature of that same month. Previous meteorological conditions extending possibly for several months may be expected, of course, to influence the quantity and distribution of the water in the soil at the beginning of the month, but it would appear premature to attempt to discuss the nature or extent of this influence until more immediate meteorological factors have been considered.

Even with these the present investigation will be limited to the average response to unit variations in the rainfall, or the temperature. It would be unreasonable to suppose that the response in drainage to a given inch of rain will be the same in a wet as in a dry month, consequently it is to be anticipated that a more elaborate non-linear formula in terms of rainfall, and possibly also in terms of temperature would give a closer prediction. It is a principal object of the present enquiry to provide material for such further studies. Nevertheless, it is believed that the simple average response to increments of rainfall and temperature, and the comparison of these averages for the different gauges and the different months of the year, will always be of more immediate interest than effects of higher order. We shall consequently study the possibilities of a prediction formula of the simple form

$$P = c + b_2 R + b_4 T, \qquad \ldots\ldots(1)$$

where c, b_2 and b_4 are constants for a given gauge in a given month of the year, and R and T stand for the total rainfall, and the monthly mean temperature derived from the readings of the maximum and minimum thermometers. Air temperatures only are available, but the variations in the monthly averages of these will certainly correspond closely to those of the mean temperature in the soil mass.

In the study of these historical gauges a further most important factor must be taken into account. As was to be expected and has long been recognised by writers on these gauges, slow changes have been going on in the condition of the soil of a kind which might well influence both the average amount of water percolating and the average response to increments of rainfall and temperature. We must therefore take time into account as an independent variate. As in the case of the other variates we shall consider only the average rate of change during the 55 years. Even this, however, leads to the introduction of three new terms. The form of regression equation finally adopted is therefore

$$P = c + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5, \qquad \ldots\ldots(2)$$

where x_1 stands for the date measured from 1900, x_2 for the rainfall measured from zero, x_3 for the product of x_1 and x_2, x_4 for the temperature in degrees F. from an arbitrary origin T_m chosen to suit convenience for each month, and x_5 is the product of x_3 and x_4. The purpose of choosing variates x_3 and x_5, each of which is the product of two of the other variates used, is to provide values not merely for the regressions of percolation upon rainfall and temperature, but for the rates of change of these regression coefficients.

For, if we substitute in this formula, which is given in terms of the variates most easy to handle arithmetically, the variates in which the results are most simply interpreted, namely

$$x_1 = t = t' + 5,$$

where t' is the time measured from 1905, the central year of the period investigated,

$$x_2 = R = \bar{R} + R',$$

where R' is the deviation of the rainfall from its average value for the month considered, then

$$x_3 = tR = (t' + 5)\,(\bar{R} + R').$$

Again $$x_4 = T - T_m = (\bar{T} - T_m) + (T - \bar{T}) = (\bar{T} - T_m) + T',$$

where T' is the deviation of the temperature of the month from its mean value, and consequently

$$x_5 = t\,(T - T_m) = (t' + 5)\,(\bar{T} - T_m + T').$$

Making these substitutions in equation (2) we have

$$P=c+b_1(t'+5)+b_2(\bar{R}+R')+b_3(t'+5)(\bar{R}+R')$$
$$+b_4(\bar{T}-T_m+T')+b_5(t'+5)(\bar{T}-T_m+T'),$$

or, more simply,

$$P=c+5b_1+b_2\bar{R}+5b_3\bar{R}+b_4(\bar{T}-T_m)+5b_5(\bar{T}-T_m)$$
$$+t'(b_1+b_3\bar{R}+b_5(\bar{T}-T_m))$$
$$+R'(b_2+5b_3)+T'(b_4+5b_5)+b_3t'R'+b_5t'T',$$

which may be written

$$P=c'+b_1't'+b_2'R'+b_3't'R'+b_4'T'+b_5't'T',$$

where $b_3'=b_3,\qquad b_5'=b_5,$

$$b_2'=b_2+5b_3,\qquad b_4'=b_4+5b_5,$$
$$b_1'=b_1+b_3\bar{R}+b_5(\bar{T}-T_m),$$
$$c'=c+5b_1+b_2\bar{R}+5b_3\bar{R}+b_4(\bar{T}-T_m)+5b_5(\bar{T}-T_m).$$

The regression formula may now be written in the simple form

$$P=(c'+b_1't)+(b_2'+b_3't')R'+(b_4'+b_5't')T', \qquad \ldots\ldots(3)$$

showing that we have obtained a simple regression equation in the two variates R' and T' representing the deviations of the observed rainfall and temperature from the average of the month in question, with the added feature that the three constants of the formula are now each of them linear functions of the time capable of representing any steady change in the values of these constants.

Returning now to equation (2) the best values of b_1, b_2, b_3, b_4 and b_5 are obtained from the solution of partial regression equations. Dr Fisher's "matrix method" has been employed for the solution of these equations, since it is not only the quickest method (especially in the present case, where we have three dependent variates P_1, P_2, P_3 indicating drainage through the 20, 40 and 60 in. gauges respectively, each of which has the same set of independent variates) of evaluating partial regression coefficients, but it also provides material for the calculation of their standard errors. The method of solution and substitution is given in Dr Fisher's *Statistical Methods for Research Workers*, Section 29(1). The advantages of the indirect method of solution there given for work involving many independent variates will be more readily appreciated if the procedure of successive substitution used to obtain the values of c_{12}, c_{13}, etc., from c_{11} be described in detail. The month of June has been chosen for this purpose.

The numerical values of the fifteen sums of squares and products of deviations of x_1, x_2, x_3, x_4 and x_5 from their respective means form the coefficients in the five equations of least squares:

$$b_1 S(x_1^2) + b_2 S(x_1 x_2) + b_3 S(x_1 x_3) + b_4 S(x_1 x_4) + b_5 S(x_1 x_5) = S(x_1 P),$$
$$b_1 S(x_1 x_2) + b_2 S(x_2^2) + b_3 S(x_2 x_3) + b_4 S(x_2 x_4) + b_5 S(x_2 x_5) = S(x_2 P),$$
$$\text{etc.},$$

by which the best values for $b_1 \ldots b_5$ may be obtained for each of the drain gauges, if its readings are substituted in the sums of products on the right of the equations. Instead of solving these equations as they stand, however, it is always preferable, when standard errors are required, to invert the matrix of coefficients by carrying out the arithmetical solution on the equations in which the right-hand side is either unity or zero. The equations required for the month of June are:

$$\left.\begin{array}{l}
+13860{\cdot}000 b_1 - 309{\cdot}920 b_2 + 27037{\cdot}110 b_3 - 255{\cdot}000 b_4 + 26020{\cdot}200 b_5 = 1, 0, 0, 0, 0 \\
-\ \ 309{\cdot}920 b_1 + 88{\cdot}002 b_2 - 438{\cdot}672 b_3 - 35{\cdot}081 b_4 - 651{\cdot}284 b_5 = 0, 1, 0, 0, 0 \\
+27037{\cdot}110 b_1 - 438{\cdot}672 b_2 + 73350{\cdot}575 b_3 - 559{\cdot}708 b_4 + 41755{\cdot}414 b_5 = 0, 0, 1, 0, 0 \\
-\ \ 255{\cdot}000 b_1 - 35{\cdot}081 b_2 - 559{\cdot}708 b_3 + 169{\cdot}899 b_4 + 719{\cdot}889 b_5 = 0, 0, 0, 1, 0 \\
+26020{\cdot}200 b_1 - 651{\cdot}284 b_2 + 41755{\cdot}414 b_3 + 719{\cdot}889 b_4 + 88516{\cdot}997 b_5 = 0, 0, 0, 0, 1
\end{array}\right\}, \text{(i)}$$

where the left-hand side is identical with that of the equations of least squares. The values of $b_1 \ldots b_5$ obtained by such sets of equations are denoted by:

$$\begin{array}{ccccc}
c_{11} & c_{12} & c_{13} & c_{14} & c_{15} \\
c_{12} & c_{22} & c_{23} & c_{24} & c_{25} \\
c_{13} & c_{23} & c_{33} & c_{34} & c_{35} \\
c_{14} & c_{24} & c_{34} & c_{44} & c_{45} \\
c_{15} & c_{25} & c_{35} & c_{45} & c_{55}
\end{array}$$

which constitutes the inverted matrix.

In order to obtain the first row or column of this matrix we substitute $c_{11}, c_{12}, \ldots$ for $b_1, b_2, \ldots$ in the first set of equations (i), and eliminating c_{15} from the first four by cross multiplication we have:

$$\left.\begin{array}{l}
+\ \ 5497{\cdot}948 c_{11} - 104{\cdot}8665 c_{12} + 13067{\cdot}596 c_{13} - 413{\cdot}0349 c_{14} = 0{\cdot}88516997 \\
-\ \ 104{\cdot}8665 c_{11} + 73{\cdot}65502 c_{12} - 116{\cdot}35295 c_{13} - 26{\cdot}36413 c_{14} = 0 \\
+13067{\cdot}596 c_{11} - 116{\cdot}35295 c_{12} + 47492{\cdot}580 c_{13} - 796{\cdot}0293 c_{14} = 0 \\
-\ \ 413{\cdot}0349 c_{11} - 26{\cdot}36413 c_{12} - 796{\cdot}0293 c_{13} + 145{\cdot}2070 c_{14} = 0
\end{array}\right\}. \ \ldots\text{(ii)}$$

From these, using the fourth equation to eliminate c_{14} from the first three by cross multiplication, we have:

$$\left.\begin{array}{l}
+\ \ 6277{\cdot}427 c_{11} - 261{\cdot}1664 c_{12} + 15687{\cdot}1853 c_{13} = 1{\cdot}28532876 \\
-\ \ 261{\cdot}1664 c_{11} + 100{\cdot}00157 c_{12} - 378{\cdot}81883 c_{13} = 0 \\
+15687{\cdot}1853 c_{11} - 378{\cdot}81883 c_{12} + 62625{\cdot}924 c_{13} = 0
\end{array}\right\}. \qquad \ldots\ldots\text{(iii)}$$

Now using the third equation to eliminate c_{13} from the first two, we have:

$$\left.\begin{aligned} +1470{\cdot}4188c_{11} - 104{\cdot}13186c_{12} &= 0{\cdot}804949012 \\ -104{\cdot}13186c_{11} + 61{\cdot}191870c_{12} &= 0 \end{aligned}\right\}, \qquad \text{......(iv)}$$

from which the value of c_{11} is at once obtained:

$$791{\cdot}342318c_{11} = 0{\cdot}492563353,$$
$$\text{or} \qquad c_{11} = 0{\cdot}0006224403.$$

The value of c_{12} is now obtained by substitution in the second equation of (iv) and its accuracy is checked by recalculating the value of c_{11} from the first equation. The value of c_{13} is computed from the last equation of (iii); c_{12} and c_{11} are then recalculated from the second and first equations respectively. The process is continued until c_{15} is evaluated and checked by at least one substitution. In this manner c_{11} is checked four times, c_{12} thrice, c_{13} twice and c_{14} once only. The values obtained by the complete process of substitution are given below to show the degree of concordance to be expected, when as above not less than seven figures are retained in the terms of the leading diagonal in the process of elimination.

c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
0·0006224403	—	—	—	—
0·0006224403	0·0010592234	—	—	—
0·0006224403	0·0010592235	−0·0001495081	—	—
0·0006224403	0·0010592236	−0·0001495081	0·0011432107	—
0·0006224403	0·0010592236	−0·0001495081	0·0011432103	−0·0001139485

This provides the values for the first column or row of the matrix, and these values are fixed and are not altered by the further process of substitution. By solving only one set of equations, we are now in a position (and this is a most important point of the matrix method) to obtain the solution of the other four equations, and through them of any system of equations with the same matrix of coefficients, by the methodical process of substitution only. Thus the values of c_{22}, c_{23}, c_{24} and c_{25} (which together with c_{12} form the second row or column of the matrix) are obtained from the solution of the equations (iv) to (i) by writing c_{12}, c_{22}, c_{23}, c_{24} and c_{25} in place of c_{11}, c_{12}, c_{13}, c_{14} and c_{15} and assigning the non-vanishing element of the right-hand side to the second equation of each group instead of to the first. The first equation of each group is now ignored. Equation (iv) becomes:

$$-104{\cdot}13186c_{12} + 61{\cdot}19187c_{22} = 0{\cdot}804949012, \qquad \text{......(iv}'\text{)}$$

from which, knowing c_{12}, c_{22} is immediately evaluated. c_{23} is next obtained from the third equation of (iii′) and its accuracy is checked by recalculating c_{22} from the second equation, c_{24} and c_{25} are computed in a similar manner from the equations (ii′) and (i′). The values of c_{22}, c_{23}, c_{24} and c_{25} are now fixed and are not further altered in the evaluation of other values of c.

The values of c_{33}, c_{34} and c_{35} are now obtained from the equations (iii), (ii) and (i) by a similar process of elimination and checking, by assigning the non-vanishing element of the right-hand side to the third equation of each group and ignoring the first *two* equations of each group. c_{44} and c_{45} are obtained from (ii) and (i), and finally c_{55} is obtained from (i) by a similar process.

The complete matrix thus evaluated is given below in units of 10^{-4}.

$$\begin{array}{rrrrr}
+\ 6{\cdot}224403 & +\ 10{\cdot}592236 & -1{\cdot}495081 & +11{\cdot}432103 & -1{\cdot}139485 \\
+10{\cdot}592236 & +149{\cdot}570185 & -1{\cdot}748515 & +47{\cdot}700023 & -1{\cdot}576288 \\
-\ 1{\cdot}495081 & -\ 1{\cdot}748515 & +0{\cdot}569165 & -\ 1{\cdot}449974 & +0{\cdot}169929 \\
+11{\cdot}432103 & +\ 47{\cdot}700023 & -1{\cdot}449274 & +94{\cdot}189000 & -3{\cdot}091617 \\
-\ 1{\cdot}139485 & -\ 1{\cdot}576288 & +0{\cdot}169929 & -\ 3{\cdot}091617 & +0{\cdot}381319
\end{array}$$

This matrix is used for a number of essential purposes, some of which we shall now discuss.

(*a*) *Calculation of partial regression coefficients.*

The regression coefficients being the solutions of equations having on the right-hand side the sums of products $S(Px_1)$, etc. (where P now indicates the deviation from the mean P) are obtained from the equations:

$$b_1 = S\,(Px_1)\,c_{11} + S\,(Px_2)\,c_{12} + S\,(Px_3)\,c_{13} + S\,(Px_4)\,c_{14} + S\,(Px_5)\,c_{15},$$

$$b_2 = S\,(Px_1)\,c_{12} + S\,(Px_2)\,c_{22} + S\,(Px_3)\,c_{23} + S\,(Px_4)\,c_{24} + S\,(Px_5)\,c_{25},$$

etc.

Hence the appropriate equations for the three different gauges are obtained merely by inserting in three linear equations the sums of products appropriate to each gauge. The values of these for the three gauges for the month of June are:

	P_1	P_2	P_3
$S\,(Px_1)$	$-161{\cdot}741$	$-155{\cdot}991$	$-147{\cdot}861$
$S\,(Px_2)$	$+\ 49{\cdot}365$	$+\ 48{\cdot}800$	$+\ 48{\cdot}115$
$S\,(Px_3)$	$-284{\cdot}809$	$-272{\cdot}203$	$-251{\cdot}176$
$S\,(Px_4)$	$-\ 22{\cdot}491$	$-\ 20{\cdot}778$	$-\ 20{\cdot}682$
$S\,(Px_5)$	$-301{\cdot}957$	$-315{\cdot}899$	$-295{\cdot}740$

The value of b_1 for the 20 in. gauge is obtained by multiplying the sums of products for P_1 in order with the elements of the first row or column of the matrix and adding; b_2 is obtained by multiplying the same sums of products with the elements of the second row or column and adding. In a similar manner b_3, b_4 and b_5 are obtained from the third, fourth and fifth rows or columns of the matrix. Using the sums of products for P_2 and P_3, the partial regression coefficients for the 40 and 60 in. gauges can be calculated. Thus from the matrix these coefficients can be computed immediately, and the special advantage and quickness of the method lies in the fact that the same matrix can be used for any number of dependent variates (having the same set of independent variates), consequently the labour of solving the regression equations afresh for each new dependent variate is saved. The values of these coefficients for the month of June are:

	P_1	P_2	P_3
b_1	+0·00289131	+0·00753417	+0·00653799
b_2	+0·55714761	+0·56295193	+0·55492154
b_3	−0·00253027	−0·00305896	−0·00262927
b_4	−0·02662319	−0·00412771	−0·00647790
b_5	+0·00124823	−0·00016493	+0·00011297

(*b*) *Calculation of standard errors of partial regression coefficients.*

An essential point of the matrix method is that it provides ready material for the calculation of standard errors. The sampling variance of the regression coefficient is obtained by multiplying the residual variance with the appropriate matrix element. The standard error is obtained from the sampling variance by taking the square root. Thus the standard error of b_1 is $s\sqrt{c_{11}}$, of b_2 is $s\sqrt{c_{22}}$, etc., where s^2 is the residual variance.

The sum of the squares of deviations from the regression equation is obtained from the sum of squares of deviations from the mean by deducting a term for each coefficient fitted:

$$S(P-P')^2 = S(P^2) - b_1 S(x_1 P) - b_2 S(x_2 P) - b_3 S(x_3 P) - b_4 S(x_4 P) - b_5 S(x_5 P).$$

The only new value to be computed is $S(P^2)$, and the values of the various terms to be deducted are obtained by multiplying $b_1, b_2, \ldots b_5$, with the corresponding sums of products $S(P_1 x_1)$, $S(P_1 x_2)$, … etc., given in § (*a*). The residual variance s^2 is obtained by dividing $S(P-P')^2$ by the appropriate degrees of freedom (49 in the present case). By multiplying the value of s^2 with the five principal diagonal elements of the matrix we at once obtain the values of the variances of the five regression coefficients. Using the same set of multipliers and s^2 for the 40 and 60 in. gauges, the standard errors of the regression coefficients for these two gauges can be calculated. Thus the standard errors of the regression coefficients for any number of dependent variates can be immediately calculated from the matrix. The numerical values of the quantities $S(P^2)$, $S(P-P')^2$, s^2, and the standard errors of the regression coefficients given in (*a*) are:

	P_1	P_2	P_3
$S(P^2)$	39·231	37·998	37·589
$S(P-P')^2$	11·261	10·730	11·095
s^2	0·229816	0·218980	0·226428
$\sigma_{b_1}=\sqrt{s^2c_{11}}$	0 0119598	0·0116754	0·0118720
$\sigma_{b_2}-\sqrt{s^2c_{22}}$	0 0586260	0·0572318	0·0581955
$\sigma_{b_3}=\sqrt{s^2c_{33}}$	0 0036165	0·0035305	0·0035899
$\sigma_{b_4}=\sqrt{s^2c_{44}}$	0·0465233	0·0454169	0·0461817
$\sigma_{b_5}=\sqrt{s^2c_{55}}$	0 0029601	0·0028897	0·0029384

A complete set of the values of s^2 for the twelve calendar months and for the three gauges is given in Table X.

(*c*) *Calculation of standard errors of b_2' and b_4'.*

b_2' and b_4' indicate the values of b_2 and b_4 at the central date 1905, and as has already been indicated they are obtained from the equations

$$b_2'=b_2+5b_3;\quad b_4'=b_4+5b_5.$$

The variances of these quantities are given by:

$$\sigma_{b_2'}{}^2=s^2(c_{22}+10c_{23}+25c_{33}),$$

$$\sigma_{b_4'}{}^2=s^2(c_{44}+10c_{45}+25c_{55}),$$

where s^2 is the residual variance. Thus the matrix provides a ready solution for the calculation of the standard errors of these quantities, or of any other quantity which is connected with the values of the b's by a linear equation. The numerical values of b_2', b_4' with their standard errors for the three gauges for the month of June are:

	P_1	P_2	P_3
b_2'	$+0·54450\pm0·05800$	$+0·54770\pm0·05660$	$+0·54177\pm0·05756$
b_4'	$-0·02037\pm0·04190$	$-0·00493\pm0·03993$	$-0·00593\pm0·04059$

The values of b_2', b_4' with the associated standard errors for all the months are given in Tables VI and VIII.

(*d*) *Calculation of standard errors of the difference between regression coefficients for the different gauges.*

One of the most important uses to which the matrix can be put is to calculate the standard error of the difference of two regression coefficients obtained from two dependent variates (having the same set of independent variates), allowing for the fact that the two sets of residuals from the two regression equations may be mutually highly correlated. The only new quantity to be evaluated for this purpose is the *residual covariance* which is computed from the sums of products of the two dependent variates in the same manner as the residual variance is obtained from the sum of squares of each of them.

The sum of products of the deviations from the regression equations for the two gauges P_1 and P_2 is obtained by deducting from the sum of the products of the deviations a term for each coefficient fitted:

$$\begin{aligned} S(P_1-P_1')(P_2-P_2') &= S(P_1P_2) - b_{1P_1}S(P_2x_1) - b_{2P_1}S(P_2x_2) \\ &\qquad - b_{3P_1}S(P_2x_3) - b_{4P_1}S(P_2x_4) - b_{5P_1}S(P_2x_5) \\ &= S(P_1P_2) - b_{1P_2}S(P_1x_1) - b_{2P_2}S(P_1x_2) \\ &\qquad - b_{3P_2}S(P_1x_3) - b_{4P_2}S(P_1x_4) - b_{5P_2}S(P_1x_5), \end{aligned}$$

where b_{P_1}, b_{P_2} indicate the values of the regression coefficients for the 20 and 40 in. gauges. The values of these terms are immediately obtained by cross-multiplication—*i.e.* by multiplying the value of b's of one gauge with the sums of products $S(Px)$ of the other, given in § (*a*). Since the two equations must give identical results, this process provides a check on the arithmetic of the calculation of regression coefficients for the 20 and 40 in. gauges from the matrix. In the same manner we can calculate the values of $S(P_1-P_1')(P_3-P_3')$ and $S(P_2-P_2')(P_3-P_3')$ and thus the values of all the regression coefficients are checked. The values of residual covariance for the different pairs of gauges are obtained by dividing these sums of products by the appropriate degrees of freedom (49 in the present case).

From the values of residual variance and covariance a quantity ψ^2 is computed from the equation which is merely the sum of the two residual variances minus twice the residual covariance, and represents the residual variance of the difference between the two gauge readings:

$$\psi^2_{P_1P_2} = s_1^2 + s_2^2 - 2p_{12},$$

where s_1^2, s_2^2 are the residual variances for the 20 and 40 in. gauges and p_{12} is the residual covariance between them. In a similar manner $\psi^2_{P_1P_3}$ and $\psi^2_{P_2P_3}$ are computed. A complete set of the values of ψ^2 for all the calendar months is given in Table XI. The standard error of the difference of the regression coefficients can now at once be obtained by multiplying ψ^2 with the appropriate matrix element and taking the square root of the product. Thus the standard error of $b_{2P_1} - b_{2P_2}$ is $\sqrt{\psi_{P_1P_2}c_{22}}$, and of

$b_{4P_1} - b_{4P_2}$ is $\sqrt{\psi^2_{P_1P_2} c_{44}}$. Their values for the month of June for the three gauges are:

	$P_1 - P_2$	$P_2 - P_3$	$P_1 - P_3$
b_2	$-0·00580 \pm 0·00971$	$+0·00803 \pm 0·00491$	$+0·00223 \pm 0·00863$
b_4	$-0·02249 \pm 0·00771$	$+0·00235 \pm 0·00390$	$-0·02014 \pm 0·00685$

The standard errors for the difference of two b_2' or two b_4' can be obtained by multiplying the ψ^2 with the appropriate expression involving matrix elements, and taking the square root of the resulting product.

Thus

$$\sigma_{(b_2'{}_{P_1} - b_2'{}_{P_2})} = \sqrt{\{\psi^2_{P_1P_2}(c_{22} + 10c_{23} + 25c_{33})\}},$$

$$\sigma_{(b_4'{}_{P_1} - b_4'{}_{P_2})} = \sqrt{\{\psi^2_{P_1P_2}(c_{44} + 10c_{45} + 25c_{55})\}}.$$

Thus the matrix provides solution for the standard errors of the difference of two regression coefficients each one of which is connected with the b's by a linear relation of any form.

The differences between the regression coefficients with their standard errors (for b_2' and b_4') for the twelve calendar months and for the three gauges are given in Tables VI and VIII.

DISCUSSION OF RESULTS.

Each month has been treated in exactly the same manner as the month of June described in detail in the preceding section. The results obtained from this preliminary analysis for all the months are classified

Table I. *Mean monthly values of rainfall, temperature and drainage.*

				Drainage		
		Temperature		20 in. gauge	40 in. gauge	60 in. gauge
Month	Rainfall R	$\bar{T}$	(T_m)	(P_1)	(P_2)	(P_3)
Jan.	2·302	37·547	(0)	1·9361	2·1139	2·0411
Feb.	2·025	38·436	(30)	1·5637	1·6728	1·6099
Mar.	1·987	41·049	(35)	1·0877	1·2123	1·1565
Apr.	2·046	45·384	(40)	0·6868	0·7655	0·7325
May	2·130	51·898	(50)	0·5517	0·6250	0·5923
June	2·164	57·076	(55)	0·5451	0·5819	0·5645
July	2·679	60·524	(55)	0·7155	0·7432	0·7034
Aug.	2·735	59·871	(55)	0·7964	0·8123	0·7669
Sept.	2·284	55·685	(50)	0·8052	0·8021	0·7501
Oct.	3·121	48·625	(40)	1·8207	1·8143	1·7080
Nov.	2·846	41·905	(35)	2·1949	2·2579	2·1576
Dec.	2·850	38·575	(30)	2·4593	2·5580	2·4768
Total: Oct.–Mar.	15·131	—	—	11·0624	11·6292	11·1499
Total: Apr.–Sept.	14·038	—	—	4·1007	4·3300	4·1097
Total: 12 months	29·169	—	—	15·1631	15·9592	15·2596
Mean	2·431	48·048	—	1·2636	1·3300	1·2550

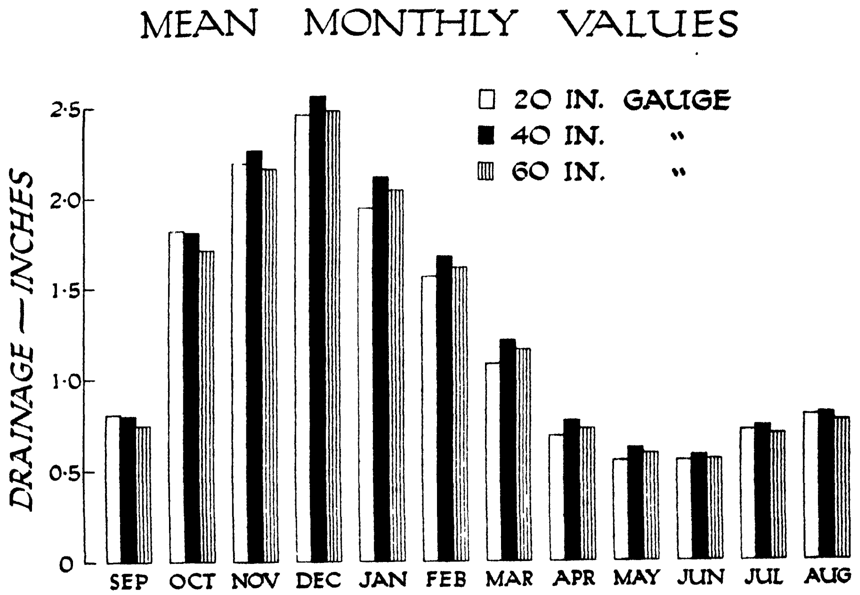
MEAN MONTHLY VALUES

Fig. 1.

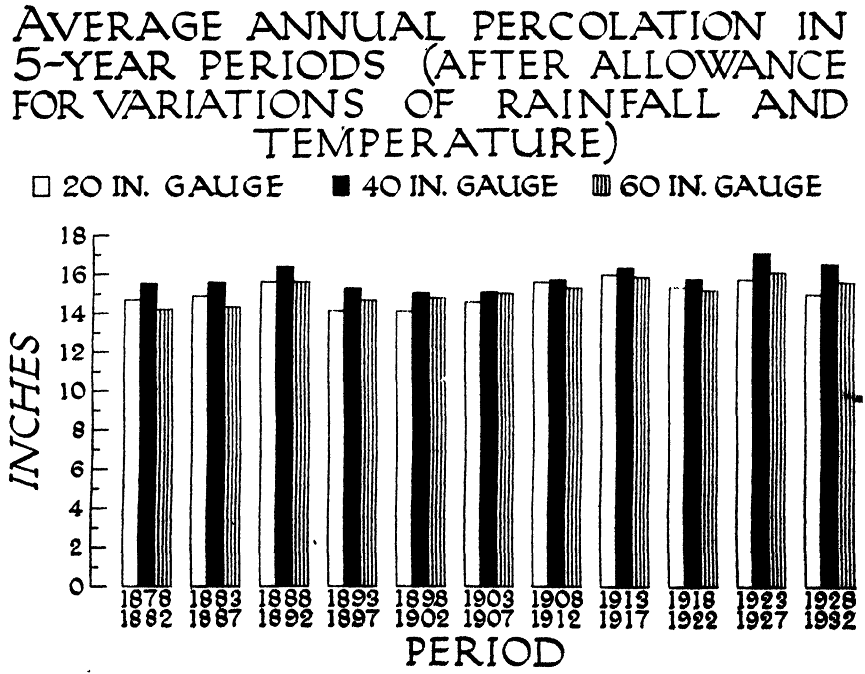
AVERAGE ANNUAL PERCOLATION IN 5-YEAR PERIODS (AFTER ALLOWANCE FOR VARIATIONS OF RAINFALL AND TEMPERATURE)

Fig. 1 *a*.

in Tables I–XIII, and are graphically illustrated in Figs. 1–8. We shall now consider the more salient features of these tables and diagrams.

Table I gives the mean monthly values of rainfall, temperature and drainage for the 55 years. Unlike temperature and drainage, the mean rainfall values do not differ much in the winter and summer. Of the winter months November and December are associated with heavy rainfall, January and February with low rainfall. In summer July and August have given high values of mean rainfall (like November and December), as compared with May and June which are as dry as January and February. The temperature values have shown remarkable regularity; they slowly rise from January to July and then gradually fall off to December. The figures shown in brackets are the values of T_m used for different months. The difference in average percolation between the warmer and the cooler months can be seen from the fact that the mean monthly rainfall from February to June is practically the same (about 2 in.), but the drainage in June is about half that of March and about a third of that of February. This is also evident from the six-monthly totals—October to March, April to September—which are practically the same for the rainfall, but the drainage of the former is about three times that of the latter.

It has been customary, and natural, to ascribe this difference to a much greater evaporation in the warmer than in the cooler months. This inference can, however, only be drawn by neglecting the variations, which are not directly observable, in the water content of the gauges. Although over a long period of years the total evaporation can be fairly estimated from the difference between the rainfall and the percolation, it should be emphasised that the distribution of evaporation over the year is not known. It will appear in Table III that when allowance is made for difference in temperature, the distribution of percolation over the year is but little altered. Further, in Table VIII it will be shown that comparing the same month in different years the effect of higher temperature is not regularly to decrease percolation, but on the whole to increase it. The inference that the smaller percolation of the summer months may be ascribed to an immediate increase in evaporation due to higher temperature is therefore questionable. The higher drainage in the cold months of winter must be at least partly accounted for by the accumulation of water during the preceding months of heavy rainfall, and the lower drainage in summer by the corresponding loss of water in the gauges during the preceding months of low rainfall.

The mean monthly drainage values for the three gauges are shown in Fig. 1 in the form of columns of appropriate height, one for each gauge. The 40 in. gauge has given higher mean drainage in all the months except the first two (September and October) than the neighbouring 20 or 60 in. gauge. Considering the 20 and 60 in. gauges only, we find that the 60 in. gauge has continually given higher mean drainage than the 20 in. gauge from December to June, while the reverse is the case from July to November.

The average annual percolation after allowance for variations of rainfall and temperature is shown for eleven 5-year periods in Fig. 1 *a*. This was constructed by applying to the mean rates of secular increase in drainage the deviations of the actual drainage recorded from that predicted from the rainfall and temperature. These deviations are individually small, but their totals show secular changes of remarkable consistency. They are predominantly positive for the first 15 years, predominantly negative for the next 15 years and for the last 25 years fluctuate somewhat irregularly. The secular changes which have been taking place in the percolatability of the three gauges are not great in absolute magnitude, but appear to be due to real changes in the condition of the soil, and, though the parallelism between the three gauges is, throughout the data, remarkably close, yet the consistent changes to which each is subject appear to be somewhat different. The diagram shows, for example, considerable consistency in the changes taking place in the differences between the percolations through the 20 and 60 in. gauges.

Table II. *Variance of rainfall, temperature and drainage.*

				Drainage	
Month	Rainfall (R)	Temperature (T)	20 in. gauge (P_1)	40 in. gauge (P_2)	60 in. gauge (P_3)
Jan.	1·01836	10·925	1·048740	1·239221	1·113851
Feb.	1·74970	13·246	1·911851	1·961407	1·866351
Mar.	1·30951	6·295	1·282258	1·440166	1·321703
Apr.	1·06629	3·672	0·634333	0·672740	0·609611
May	1·17914	4·015	0·511499	0·563407	0·473982
June	1·62963	3·146	0·726500	0·703667	0·696092
July	2·09499	5·549	0·633222	0·672981	0·605815
Aug.	2·15692	4·157	1·191555	1·187259	1·081111
Sept.	2·07156	4·195	1·225203	1·288425	1·230166
Oct.	2·56493	6·436	2·152610	2·180554	2·011629
Nov.	1·57626	6·206	1·566037	1·713018	1·606555
Dec.	2·56809	10·350	2·755406	2·661222	2·520259

Table II gives the variance of monthly values of rainfall, temperature and drainage for the 55 years. Like the mean values, the rainfall variance shows higher values in autumn than in spring; its value is small from

January to June, and comparatively greater from July to December (with the exception of November). The temperature variance is much greater in the winter months December, January and February, as compared with other months of the year, the highest value in February being about four times the lowest value in June. It is interesting to note that there is a remarkable oscillation in the rainfall variance, particularly in the winter months which is reflected in the variances of the drainage shown diagrammatically in Fig. 2. Comparing the three gauges

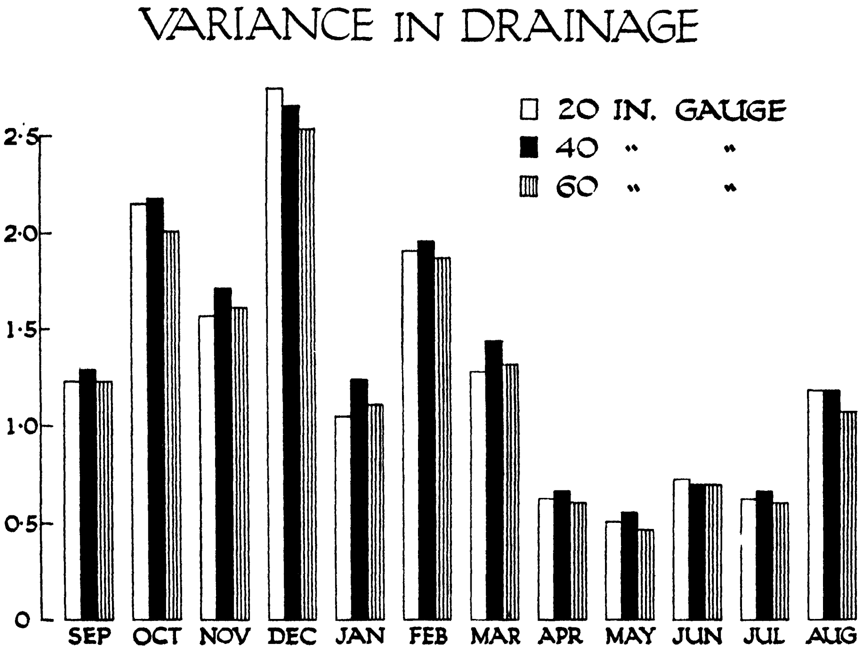

Fig. 2.

we find that the 40 in. gauge has given greater variability than either the 20 or 60 in. gauge. Considering the extreme gauges 20 and 60 in. only, we find that, from September to March, the 60 in. gauge has shown greater variability than the 20 in. gauge in alternate months, while from April to August the 20 in. gauge has shown continuously greater variability than the 60 in. gauge. A distinct seasonal effect exists in the drainage variance values, April to September having yielded exceptionally low values as compared with other months, a fact which can clearly be seen from Fig. 2, and corresponds with the lower mean drainage.

Table III and Fig. 3 give the values of drainage under standard conditions, the standard for rainfall adopted is approximately the mean monthly rainfall for 55 years, 2·5 in., and the mean monthly temperature, 48° F. The standardised drainage has been obtained from the regression equations of form (2) for different months using the value of $x_1 = 5$, so that the values calculated are those expected for the year 1905,

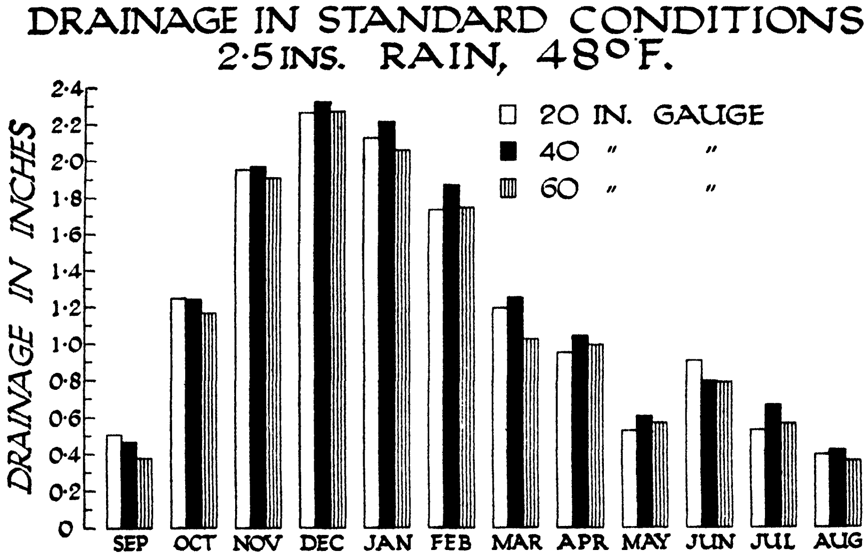

Fig. 3.

Table III. *Drainage under standard conditions: rainfall* 2·5 *in., temperature* 48° *F.*

Month	20 in. gauge P_1	40 in. gauge P_2	60 in. gauge P_3
Jan.	2·120	2·210	2·057
Feb.	1·734	1·863	1·742
Mar.	1·196	1·256	1·229
Apr.	0·953	1·021	0·988
May	0·531	0·605	0·576
June	0·904	0·793	0·786
July	0·536	0·641	0·567
Aug.	0·399	0·422	0·365
Sept.	0·509	0·469	0·380
Oct.	1·246	1·244	1·164
Nov.	1·948	1·965	1·912
Dec.	2·264	2·320	2·268
Total: Oct.–Mar.	10·508	10·858	10·372
Total: Apr.–Sept.	3·832	3·951	3·662
Mean drainage per month	1·19108	1·23408	1·16950

the mid-point of the period 1878–1932. The values of c (constant in the regression equation (2)) for the different months and for the three gauges are given in Table XIII.

Comparing the values in Table III with those in Table I we find that, in all the gauges, the values of Table III are numerically lower from July to December and higher from January to June, with the exception of May; the apparent reason is that the standard rainfall used is higher than the actual (about 2 in.) for these months (January to June). It is a very remarkable fact that the seasonal effect remains practically the same after standardisation as before—the drainage values in the summer months being much lower than in the winter months. This is also clear from the totals of six-monthly periods—October to March, April to September—the value for the former being about three times the latter. If the behaviour of the drain gauge could be expected to depend only on the meteorology of the current month, these values should not have differed very much from month to month. The striking disparity with the expectation shows that much of the variation in drainage in the course of the year must be ascribed to the influence of the weather belonging not to the month of drainage but to a previous period. Comparing the three gauges, we find that, like the mean monthly drainage, the drainage under standard conditions is greater for the 40 in. gauge than for the 20 or 60 in. gauge.

Table IV. *Values of c'.*

Month	20 in. gauge P_1	40 in. gauge P_2	60 in. gauge P_3
Jan.	1·9043	2·0677	2·0073
Feb.	1·5622	1·6708	1·6086
Mar.	1·0936	1·2188	1·1625
Apr.	0·6807	0·7641	0·7302
May	0·5523	0·6280	0·5929
June	0·5366	0·5640	0·5502
July	0·7136	0·7406	0·7001
Aug.	0·7985	0·8170	0·7727
Sept.	0·7993	0·7963	0·7443
Oct.	1·7905	1·7829	1·6800
Nov.	2·1942	2·2575	2·1564
Dec.	2·4479	2·5528	2·4682
Total	15·0737	15·8605	15·1734
Mean	1·25614	1·32170	1·26444

The values of the three constants c', b_2' and b_4' of equation (3) obtained for each month, for the three gauges, together with the values of b_1', b_3' and b_5' which represent the steady change in these constants with time are tabulated in Tables IV–IX. We shall now discuss the significance of these constants, and the anomalous behaviour of some of them.

Table V. b_1'. *Regression of drainage on t'.*

Month	20 in. gauge P_1	40 in. gauge P_2	60 in. gauge P_3
Jan.	+0·00214	+0·00136	+0·00053
Feb.	+0·00266	+0·00143	+0·00290
Mar.	+0·00146	−0·00104	−0·00058
Apr.	+0·00228	+0·00380	+0·00453
May	−0·00245	−0·00196	−0·00042
June	+0·00001	+0·00060	+0·00108
July	+0·00123	+0·00246	+0·00271
Aug.	+0·00388	+0·00594	+0·00636
Sept.	+0·00282	+0·00411	+0·00469
Oct.	−0·00042	+0·00132	+0·00205
Nov.	+0·00070	+0·00087	+0·00155
Dec.	+0·00359	+0·00360	+0·00405
Total	+0·01790	+0·02249	+0·02945
Mean	+0·00149	+0·00187	+0·00245

Table IV showing the values of c', the expectation for the mean rainfall and temperature of each month, is in many respects similar to Table I, and indicates clearly the seasonal effect and the abnormal behaviour of the 40 in. gauge. Considering these values in conjunction with the values of b_1' (Table V) representing their steady rate of change, the following interesting points may be noted:

(i) The differences in the values of c' for the 40 in. gauge and the 20 in. gauge for January, February and March are likely to become smaller in later years in view of the fact that the values of b_1', though small, are numerically less for the former than for the latter, particularly the value for the month of March for the 40 in. gauge is negative.

(ii) From April to October the difference $P_2 - P_1$ for c' is expected to become larger with advance of date in view of the larger value of b_1' for the 40 in. gauge.

(iii) The values of b_1' from April to December gradually increase from the 20 to the 60 in. gauge, consequently the differences in the values of c' for the three gauges would be less marked in later years.

(iv) As the numerical values of the differences in the values of b_1' for the different gauges are all very small the final values of c' for the year 1932 will not be much different from their values for the central date 1905.

The partial regression coefficients b_2' (regression on rainfall) are given in Table VI and their steady rate of change in Table VII. From the study of these tables the following very interesting points emerge.

(i) For all gauges the regression coefficients are higher in the winter

Table VI. b_2'. *Regression of drainage on rainfall* (*R*).

Month	P_1	P_2	P_3	$P_1 - P_2$	$P_2 - P_3$	$P_1 - P_3$
Jan.	0·96729 ± 0·03848	1·01274 ± 0·06123	0·98164 ± 0·05290	−0·04545 ± 0·03758	−0·03110 ± 0·02600	−0·01435 ± 0·03720
Feb.	1·03995 ± 0·03693	1·04871 ± 0·03940	1·02950 ± 0·03659	−0·00876 ± 0·02456	+0·01921 ± 0·01238	+0·01045 ± 0·01393
Mar.	0·92797 ± 0·05611	0·97816 ± 0·06529	0·94363 ± 0·06123	−0·05019 ± 0·01668	+0·03453 ± 0·00979	−0·01566 ± 0·01688
Apr.	0·67706 ± 0·04956	0·68270 ± 0·05495	0·64398 ± 0·05457	−0·00564 ± 0·01245	−0·03872 ± 0·01638	+0·03308 ± 0·01763
May	0·61128 ± 0·04133	0·63423 ± 0·04309	0·58589 ± 0·04084	−0·02295 ± 0·01010	+0·04834 ± 0·00973	+0·02539 ± 0·01044
June	0·54450 ± 0·05800	0·54770 ± 0·05660	0·54177 ± 0·05756	−0·00320 ± 0·00961	−0·00593 ± 0·00486	+0·00273 ± 0·00853
July	0·49579 ± 0·04012	0·49820 ± 0·04395	0·46855 ± 0·04361	−0·00241 ± 0·01002	+0·02965 ± 0·00529	+0·02724 ± 0·00939
Aug.	0·69363 ± 0·04891	0·69169 ± 0·05060	0·66294 ± 0·04855	+0·00194 ± 0·00682	+0·02875 ± 0·00482	+0·03069 ± 0·00796
Sept.	0·72937 ± 0·03738	0·73798 ± 0·04301	0·71706 ± 0·04384	−0·00861 ± 0·00792	+0·02092 ± 0·00418	+0·01231 ± 0·01006
Oct.	0·87745 ± 0·03092	0·88269 ± 0·03422	0·84146 ± 0·03708	−0·00524 ± 0·01142	+0·04123 ± 0·00892	+0·03599 ± 0·01273
Nov.	0·97128 ± 0·02757	1·01513 ± 0·03085	0·97431 ± 0·03225	−0·04385 ± 0·01496	+0·04082 ± 0·01105	−0·00303 ± 0·01602
Dec.	0·98500 ± 0·02676	0·96900 ± 0·02590	0·93408 ± 0·02733	−0·01600 ± 0·01200	−0·03492 ± 0·00922	+0·05092 ± 0·01464
Mean	0·79338	0·80824	0·77707			

Table VII. b_3. *Change of regression on rainfall with time, or regression of drainage on Rt* (*rainfall sequence*).

Month	P_1	P_2	P_3
Jan.	−0·00042 ± 0·00270	−0·00203 ± 0·00429	−0·00210 ± 0·00370
Feb.	−0·00223 ± 0·00245	−0·00321 ± 0·00261	−0·00213 ± 0·00242
Mar.	−0·00211 ± 0·00433	−0·00417 ± 0·00504	−0·00450 ± 0·00473
Apr.	+0·00186 ± 0·00314	+0·00035 ± 0·00339	+0·00095 ± 0·00337
May	+0·00403 ± 0·00221	+0·00224 ± 0·00230	+0·00401 ± 0·00218
June	−0·00253 ± 0·00361	−0·00305 ± 0·00353	−0·00263 ± 0·00359
July	+0·00314 ± 0·00262	+0·00318 ± 0·00288	+0·00348 ± 0·00285
Aug.	+0·00047 ± 0·00259	+0·00145 ± 0·00268	+0·00198 ± 0·00257
Sept.	−0·00247 ± 0·00232	−0·00219 ± 0·00267	−0·00208 ± 0·00273
Oct.	−0·00488 ± 0·00172	−0·00476 ± 0·00193	−0·00419 ± 0·00215
Nov.	+0·00053 ± 0·00164	+0·00005 ± 0·00183	+0·00065 ± 0·00191
Dec.	+0·00391 ± 0·00174	+0·00427 ± 0·00168	+0·00498 ± 0·00178
Total: Oct.–Mar.	−0·00520	−0·00579	−0·00729
Total: Apr.–Sept.	+0·00450	+0·00198	+0·00580
Mean	−0·000058	−0·000317	−0·000124

than in the summer months; particularly the value in July is about half that of February, showing that there is greater response to rainfall in the winter than in the summer months. It is interesting that the value for February is greater than unity, but in view of the large negative value of b_3, the value falls off in succeeding years—thus for 1930 the values for the 20, 40 and 60 in. gauges are 0·98425, 0·96846 and 0·97800 respectively.

(ii) Considering the three gauges separately we find that P_2 is greater than either P_1 or P_3 (with the exception of August and December) indicating that in the 40 in. gauge there is, on the average, greater amount of drainage for an extra inch of rain than in the two neighbouring gauges. Had the 60 or the 20 in. gauge behaved exceptionally, we would have attributed the cause to the difference in the depths of the gauges, but as the 40 in. gauge has shown the abnormal effect, we suspect that the difference, like that in the average drainage, must be due to soil heterogeneity.

(iii) It is remarkable that the three gauges have behaved in a similar manner in response to rainfall, in spite of the great difference in their depth. Nevertheless, it is interesting to note that many of the small differences in the regression coefficients are significant as can be seen from the tabulated values of P_1-P_2, P_2-P_3, P_1-P_3 with their associated standard errors. These small differences would not be considered significant in view of the large standard errors associated with each of the regression coefficients, but due to the fact that the residuals from the regression equations are highly correlated, the standard errors associated with P_1-P_2, P_2-P_3 or P_1-P_3 are comparatively much smaller than would be expected if the residuals were independent. The significant differences P_2-P_3 are shown by a cross-hatched portion of the histograms in Fig. 4, which shows diagrammatically these coefficients for the different months. From the figure it is clear that in nine months out of twelve this difference is significant, and even in the case of the three months (January, February and June), where it is non-significant, the difference P_2-P_3 as in other months is positive, thus showing in an undoubted manner that the percolatability of the 40 in. gauge is decidedly higher than that of the 60 in. gauge. As the question of the significance of the difference of regression coefficients is of considerable importance and of wider application, it would be worth while if we consider in detail one or two months. The values of b_2' for the three gauges for the month of November are:

20 in. gauge	40 in. gauge	60 in. gauge
$0·97128 \pm 0·02757$	$1·01513 \pm 0·03085$	$0·97431 \pm 0·03225$

Judging from their standard errors, their values do not differ significantly from unity, consequently the difference between any pair of them might at first thought not be considered significant. But actually the small difference +0·04082 between the 40 and 60 in. gauge values is about four times its standard error (±0·01105). The reason for this is that the residual covariance is nearly as great as the residual variance for any one of them, or in other words, the residuals obtained after fitting the regression formula are highly and positively correlated. The values of the correlations between the 40 and 60 in. gauges before and after elimination of regression are +0·9969 and +0·8723 respectively. In a similar manner the small difference $P_2-P_3=+0{\cdot}02092$ for September is about five times its standard error (±0·00418), for in this case the correlation between the residuals is even greater, the actual value being +0·9721.

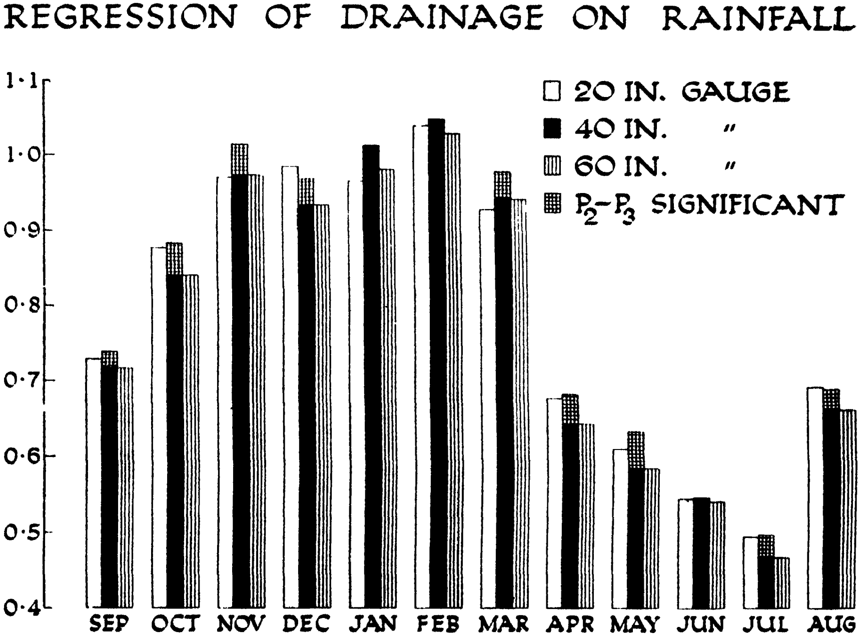

Fig. 4.

The drain gauges may be compared to the neighbouring agricultural fields, and the example shows that conclusions with respect to the effect of weather on the yields of neighbouring plots similarly treated should be drawn with considerable caution. It may happen that the yields after eliminating the effect of some element of weather, such as rainfall, may be highly correlated, and consequently the small difference between the regression coefficients may be highly significant, although considered separately each one of their standard errors may be large.

(iv) The values of b_3 given in Table VII indicate the change of regression on rainfall with date. Thus the value $-0{\cdot}00042$ indicates that the regression on drainage for the 20 in. gauge in the month of January decreases at the rate of 0·00042 every year—thus its value in 1885 and in 1925 becomes 0·96813 and 0·96645 respectively, the value for the central date 1905 being 0·96729. All the values of b_3 are small and non-significant, except October and December, giving negative and positive significant values respectively. These small values of b_3 will not greatly affect the numerical values of the regression coefficients (b_2) themselves in succeeding years, but the difference between them for the different gauges would be materially altered in several cases. Thus $P_1 - P_2$ for December in the year 1930 would become $+0{\cdot}00700$, which is about half its value $+0{\cdot}001600$ for 1905. This is due to the fact that the value of b_3 ($+0{\cdot}00391$) for P_1 which has given higher value of b_2' is lower than that ($+0{\cdot}00427$) for P_2 giving lower value of b_2', and if similar conditions hold good beyond 1932, the difference may disappear. For the same reason $P_1 - P_3$ would also become in 1930 about half its mean value (in 1905). The average values of b_3 given at the bottom of the table are negative for all the three gauges, and they represent the rate of change

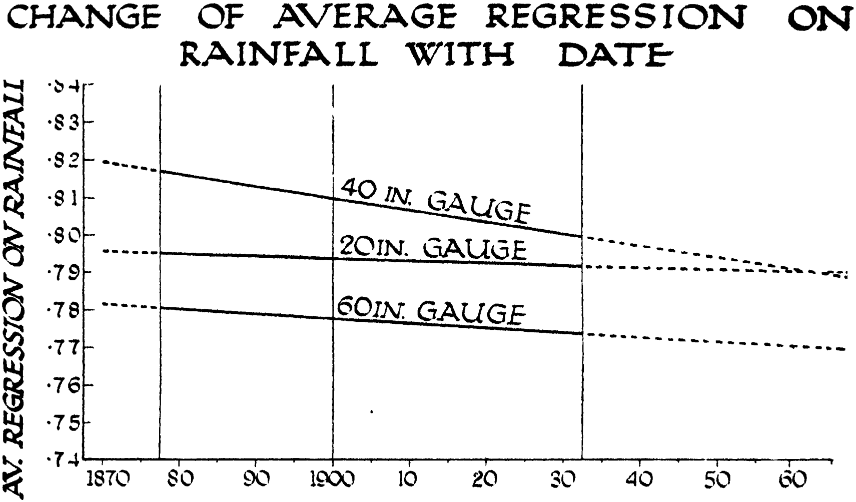

Fig. 5.

of average values of b_2' given at the bottom of Table VI. This annual rate of change of average regression is illustrated graphically in Fig. 5. It shows that the difference between the gauges was considerably greater in the year 1878, but continuously became smaller in the succeeding years—particularly the difference between the 20 and the 40 in. gauges for the year 1932 is about one-quarter of that in 1878. If similar conditions continue it is expected that the difference may vanish in the near future.

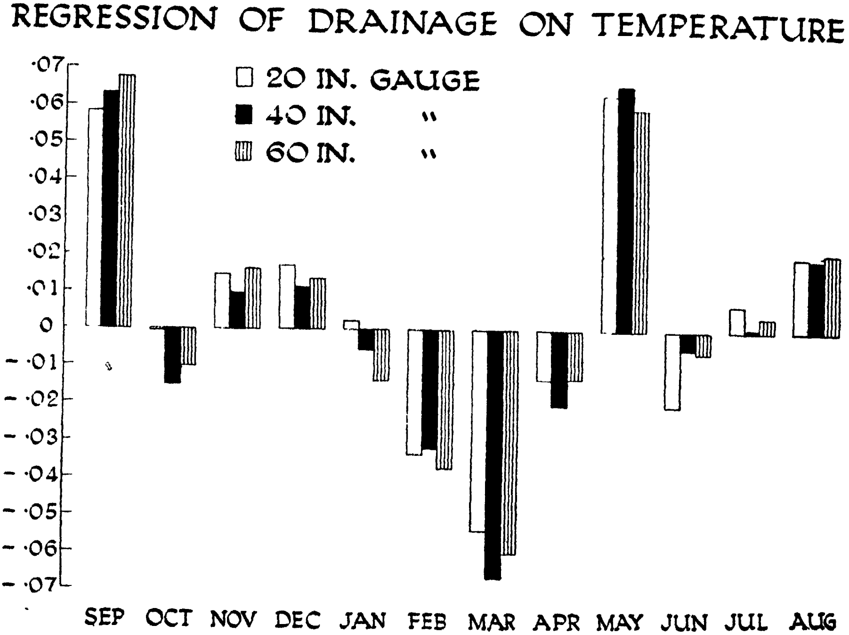

Fig. 6.

Table VIII gives the values of the regression of drainage on temperature and their steady change is indicated by values of b_5 given in Table IX. These have yielded very remarkable and in some cases paradoxical results. The general trend in the values for the three gauges can be seen from Fig. 6. Starting with a high positive value for September, we pass through a small negative value for October to small positive values for November, December and January (P_1 only), after which we get a succession of negative values, two of which for February and March are significant; after April there is a sudden return to a large positive and significant value for May, followed by a small negative value for June, and positive values for July and August.

Table VIII. b_4'. *Regression of drainage on temperature.*

Month	P_1	P_2	P_3	P_1-P_2	P_2-P_3	P_1-P_3
Jan.	+0·00232 ±0·01294	−0·00556 ±0·02006	−0·01381 ±0·01779	+0·00788 ±0·01264	+0·00825 ±0·00875	+0·01613 ±0·01003
Feb.	−0·03361 ±0·01361	−0·03194 ±0·01452	−0·03717 ±0·01348	−0·00167 ±0·00905	+0·00523 ±0·00456	+0·00356 ±0·00513
Mar.	−0·05377 ±0·02416	−0·06679 ±0·02811	−0·06000 ±0·02636	+0·01302 ±0·00718	−0·00679 ±0·00382	+0·00625 ±0·00727
Apr.	−0·01339 ±0·02647	−0·02022 ±0·02945	−0·01314 ±0·02914	+0·00683 ±0·00665	−0·00708 ±0·00875	−0·00025 ±0·00942
May	+0·06332 ±0·02277	+0·06591 ±0·02375	+0·05948 ±0·02250	−0·00259 ±0·00557	+0·00643 ±0·00436	+0·00384 ±0·00510
June	−0·02037 ±0·04190	−0·00493 ±0·03993	−0·00593 ±0·04059	−0·01544 ±0·00678	+0·00100 ±0·00343	−0·01444 ±0·00602
July	+0·00712 ±0·02440	+0·00080 ±0·02674	+0·00395 ±0·02653	+0·00632 ±0·00610	−0·00315 ±0·00322	+0·00317 ±0·00566
Aug.	+0·01996 ±0·03410	+0·01963 ±0·03528	+0·02122 ±0·03385	+0·00033 ±0·00475	−0·00159 ±0·00336	−0·00126 ±0·00555
Sept.	+0·05831 ±0·02630	+0·06332 ±0·03015	+0·06762 ±0·03073	−0·00501 ±0·00555	−0·00430 ±0·00286	+0·00931 ±0·00706
Oct.	−0·00062 ±0·01980	−0·01518 ±0·02191	−0·01016 ±0·02375	+0·01456 ±0·00731	−0·00502 ±0·00571	+0·00954 ±0·00815
Nov.	+0·01469 ±0·01366	+0·00962 ±0·01528	+0·01517 ±0·01597	+0·00507 ±0·00741	−0·00550 ±0·00572	−0·00048 ±0·00802
Dec.	+0·01702 ±0·01398	+0·01131 ±0·01257	+0·01341 ±0·01326	+0·00571 ±0·00582	−0·00210 ±0·00447	+0·00361 ±0·00710
Total	+0·06098	+0·02597	+0·04064			
Mean	+0·00508	+0·00216	+0·00339			

Table IX. b_5. *Change of regression on temperature with time or regression of drainage on Tt (temperature sequence).*

Month	P_1	P_2	P_3
Jan.	+0·00182 ±0·00069	+0·00208 ±0·00110	+0·00229 ±0·00095
Feb.	+0·00033 ±0·00093	+0·00052 ±0·00099	+0·00038 ±0·00092
Mar.	−0·00141 ±0·00160	−0·00122 ±0·00186	−0·00101 ±0·00174
Apr.	−0·00085 ±0·00187	−0·00024 ±0·00202	−0·00012 ±0·00200
May	+0·00002 ±0·00145	−0·00037 ±0·00151	+0·00026 ±0·00143
June	+0·00125 ±0·00296	−0·00016 ±0·00289	+0·00011 ±0·00294
July	+0·00238 ±0·00179	+0·00200 ±0·00196	+0·00192 ±0·00195
Aug.	+0·00097 ±0·00219	+0·00106 ±0·00222	+0·00076 ±0·00213
Sept.	−0·00251 ±0·00145	−0·00284 ±0·00167	−0·00294 ±0·00171
Oct.	+0·00148 ±0·00127	+0·00164 ±0·00142	+0·00148 ±0·00159
Nov.	+0·00011 ±0·00089	+0·00069 ±0·00099	+0·00078 ±0·00104
Dec.	−0·00017 ±0·00075	−0·00069 ±0·00073	−0·00063 ±0·00077
Total: Oct.–Mar.	+0·00216	+0·00302	+0·00329
Total: Apr.–Sept.	+0·00126	−0·00055	−0·00001
Mean	+0·003420	+0·002470	+0·003280

These regression coefficients show the response to temperature and indicate the average effect of an additional increment of 1° F. From reasoning *a priori* it is to be expected that an additional degree of temperature will cause greater evaporation and less drainage in all months; moreover, its effect would be greater in summer months than in winter, consequently we would have expected all the regression coefficients to be negative for all months and higher numerically in summer than in winter. But contrary to all expectations July and August, which are usually the hottest months in the year, instead of yielding high negative coefficients have given small *positive* values with the added feature that their rate of change as indicated by the values of b_5 are also positive, showing that their values in the succeeding years will tend to be positive and greater in magnitude. Thus the value $+0{\cdot}01996$ for August for P_1 would become $+0{\cdot}03936$ for 1925.

By far the most interesting and paradoxical result however is yielded by May where the value of b_2' is positive and highly significant for all the three gauges. The value for the 40 in. gauge is higher than the 20 or 60 in. gauges, but the small differences between them are not significant. It is interesting to note that the values of b_5 are positive for the 20 and 60 in. gauges, but negative for the 40 in. gauge, showing that small differences between the regression coefficients in 1905 will become small with the advance of date. However the negative value for P_2 $(-0{\cdot}00037)$ is small and does not change the sign of b_4, its value for 1932 being $+0{\cdot}05592$.

The second remarkable month, September, reveals a different story. Its value like that of May is large, positive and significant but due to the large negative and significant value of b_5, it not only is falling off rapidly but actually changes its sign during the period of observation. Thus the high positive value $+0{\cdot}05831$ for P_1 becomes a low negative value $-0{\cdot}00444$ in 1930. For a similar reason, the small and negative values for P_2 and P_3 in January become large and positive values in 1930—the actual values being $+0{\cdot}04744$ and $+0{\cdot}04344$. In the month of March the three negative values $-0{\cdot}05377$, $-0{\cdot}06679$ and $-0{\cdot}06000$ become $-0{\cdot}08902$, $-0{\cdot}09729$ and $-0{\cdot}08525$ respectively in 1930. In this respect the regression on temperature differs from the regression on rainfall, where we found that due to the small values of b_3 (as compared with b_2) there was very slow change in the regression on rainfall with date.

The differences between regression coefficients for the different gauges P_1-P_2, P_2-P_3 and P_1-P_3 are all small and non-significant except P_1-P_2 and P_1-P_3 for June, which is due to the comparatively high though non-significant negative value $-0{\cdot}02037$ for P_1. It may be noted however that this negative value is associated with high positive value $+0{\cdot}00125$ of b_5, changing its value to $+0{\cdot}01088$ for 1930. In general, if we thus consider the different values of b_4' in conjunction with their rate of change, we can divide them into two main classes—the first class consisting of three months, February, March and April, giving negative values for 1905 and 1930; and secondly the nine months, May to December and January, all of which (except September) give positive values with change of date.

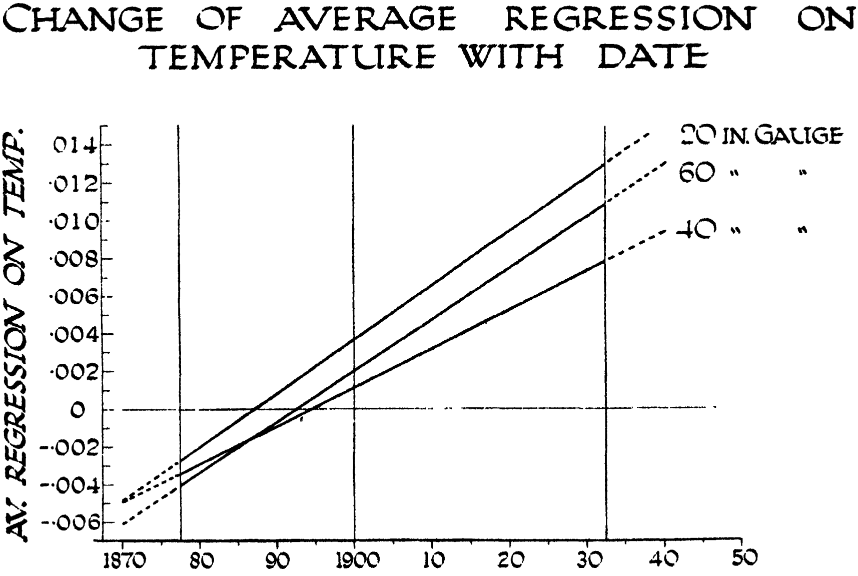

Fig. 7.

The average monthly regressions and their rates of change are all positive for all the three gauges—the actual value and its rate of change being least for the 40 in. gauge. Their trend at different dates can be seen from Fig. 7. They are all negative to begin with, but soon become positive, the difference between the 20 and 40 in. gauges being greater than in the other pairs.

Table X gives the values of the residual variance and shows how much of the variance in drainage for each month has not been removed by the regression formula for that month, and remains to be accounted for by other factors. Comparing these values with those of Table II, we find that unlike the variance, its values for November and December are smaller than in other months, and this seasonal trend becomes more marked if we regard them as percentages of the original variance. Considering the variation between gauges we find that $P_2 > P_3 > P_1$ from January to August (except June), while for the three months, September, October and November, $P_3 > P_2 > P_1$.

Table X. *Residual variance s^2.*

Month	20 in. gauge P_1	40 in. gauge P_2	60 in. gauge P_3
Jan.	0·074694	0·189041	0·141102
Feb.	0·118153	0·134388	0·115918
Mar.	0·187755	0·254143	0·223490
Apr.	0·129020	0·158633	0·156408
May	0·099673	0·108410	0·097367
June	0·229816	0·218980	0·226428
July	0·138735	0·166551	0·163898
Aug.	0·218551	0·233939	0·215367
Sept.	0·131775	0·174510	0·181347
Oct.	0·125429	0·153551	0·180592
Nov.	0·060857	0·076204	0·083215
Dec.	0·066102	0·061918	0·068939

The values of ψ^2 given in Table XI may be regarded as the values of residual variance of the difference between the pairs of gauges. Thus the values $\psi^2_{P_1-P_2}$ indicate the amount of variance not accounted for by the regression equation fitted to the differences $P_1 - P_2$. As would be expected, the values of $\psi^2_{P_2-P_3}$ are smaller than for the other two sets of pairs, on account of the comparatively higher correlation between the residuals of the 40 and 60 in. gauges. They also show a marked seasonal effect—the values being considerably smaller in summer.

Table XI. *Values of ψ^2.*

$\psi^2_{P_1-P_2} = (s_1^2 + s_2^2 - 2p_{12})$.

Month	$\psi^2_{P_1-P_2}$	$\psi^2_{P_2-P_3}$	$\psi^2_{P_1-P_3}$
Jan.	0·071205	0·034103	0·047592
Feb.	0·052255	0·013286	0·016805
Mar.	0·016592	0·004695	0·017001
Apr.	0·008143	0·011103	0·016326
May	0·005961	0·003491	0·005000
June	0·006306	0·001612	0·004978
July	0·008674	0·002409	0·007449
Aug.	0·004246	0·002122	0·005796
Sept.	0·005917	0·001571	0·009572
Oct.	0·017102	0·010429	0·021245
Nov.	0·017919	0·010673	0·021000
Dec.	0·013286	0·007837	0·019775

The values of residual percentage variance given in Table XII show a remarkable regularity. Their values are comparatively much smaller in October to February, showing that the regression formula has given greater precision in winter than in summer, and that the meteorological

Table XII. *Residual percentage variance.*

	20 in. gauge (P_1)		40 in. gauge (P_2)		60 in. gauge (P_3)	
Month	Observed	Harmonic curve	Observed	Harmonic curve	Observed	Harmonic curve
Jan.	7·1222	4·1283	15·2548	6·9752	12·6679	6·3179
Feb.	6·1799	8·7165	6·8515	11·5175	6·2109	10·9524
Mar.	14·6424	14·5984	17·6467	17·1163	16·9092	16·9649
Apr.	20·3394	20·1976	23·5800	22·2710	25·6569	22·7439
May	19·4863	24·0137	19·2418	25·6002	20·5423	26·7407
June	31·6333	25·0247	31·1198	26·2125	32·5284	27·8853
July	21·9094	22·9587	24·7482	23·9428	27·0541	25·8696
Aug.	18·3416	18·3705	19·7041	19·4005	19·9208	21·2352
Sept.	10·7553	12·4886	13·5444	13·8017	14·7416	15·2227
Oct.	5·8268	6·8894	7·0418	8·6470	8·9774	9·4437
Nov.	3·8860	3·0733	4·4485	5·3178	5·1815	5·4468
Dec.	2·3990	2·0623	2·3267	4·7056	2·7353	4·3023
Mean	13·5435		15·4590		16·0938	

factors considered can account for the drainage in winter far more satisfactorily than in summer. In December about 98 per cent. of the drainage is accounted for by the regression formula, while in June only about 70 per cent. can be explained by the meteorology of the current month. These values have indicated a similar variability between the different gauges as is shown by residual variance values of Table X. These values show a genuine cyclic change, consequently harmonic curves of the form

$$P = \bar{P} + A \sin \theta + B \cos \theta,$$

where θ is zero at the mid-date of December, were fitted to these values and are shown graphically in Fig. 8. It shows that, in general, $P_1 > P_2 > P_3$, and the differences between the gauges are more marked in the central portions of the curves, which correspond to the summer months.

The values of $\bar{P}$, A, B and the analysis of variance for the three gauges are:

	P_1	P_2	P_3
$\bar{P}$	13·5435	15·4590	16·0938
A	1·05492	1·65733	0·87109
B	−11·48117	−10·75345	−11·79145
A^2+B^2	132·93012	118·38343	139·79709

Analysis of variance (variance contributed by harmonic terms).

				P_2		P_3	
Variance due to	Degrees of freedom	Sum of squares	Mean square	Sum of squares	Mean square	Sum of squares	Mean square
Harmonic terms	2	797·58072	398·79	710·30058	355·15	838·7825	419·39
Deviation from harmonic curve	9	85·62331	9·51	166·65056	18·52	137·4025	15·27
Total	11	883·20403	80·29	876·95114	79·72	976·1850	88·74

The sum of squares removed by the harmonic terms are given by $6(A^2+B^2)$.

It is extremely interesting to note that the major portion of the cyclic change is accounted for by the harmonic curve. Of the total sum of squares about 90 per cent. is accounted for by the two degrees of freedom due to the harmonic curve for the 20 in. gauge, 81 per cent. for the 40 in. gauge and 86 per cent. for the 60 in. gauge; leaving about 10 per cent. for the 20 in. gauge, 19 per cent. for the 40 in. gauge and 14 per cent. for the 60 in. gauge to be accounted for by other causes. It is remarkable to note that the percentage variance *not* accounted for by the harmonic curve is greatest for the 40 in. gauge, showing that it still behaves in an abnormal manner.

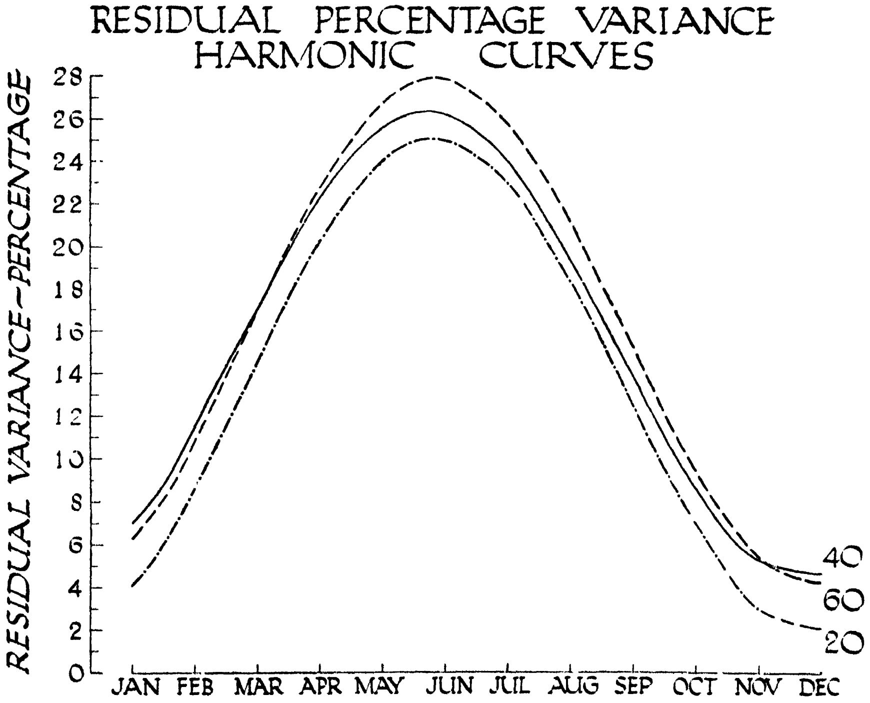

Fig. 8.

It is interesting to note that the values of $\bar{P}$ indicating the mean percentage residual variance increase with the depth of the gauge, although no simple relation exists between these values and the depth.

Table XIII. *Values of c (c in the regression equation* (2), *i.e.* $P = c + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5$).

Month	P_1	P_2	P_3
Jan.	–0·08338	0·35171	0·66822
Feb.	–0·28250	–0·20169	–0·18308
Mar.	–0·49607	–0·39416	–0·42209
Apr.	–0·64786	–0·54583	–0·53288
May	–0·81481	0·81818	–0·72162
June	–0·61408	–0·64887	–0·64283
July	–0·55232	–0·51298	–0·49092
Aug.	–1·18496	–1·15416	–1·12978
Sept.	–1·31159	–1·37538	–1·40846
Oct.	–0·95291	–0·85117	–0·87034
Nov.	–0·66367	–0·67795	–0·69283
Dec.	–0·47471	–0·29257	–0·28521

SUMMARY.

1. Partial regression equations representing the average drainage observed in any month in terms of the temperature and rainfall of that month, and including terms representing the mean secular rate of change of the drainage discharge and of its regression coefficients on rainfall and temperature, have been fitted to the thirty-six series of observations provided by the three Rothamsted drain gauges in the twelve months of the year.

2. An account is given of adequate and direct numerical methods of handling equations involving observed quantities, and chosen functions of them, as independent variates, and of calculating standard errors appropriate to the several sorts of comparison which are to be made.

3. In the absence of direct knowledge of the amount of water contained from time to time in the soil mass of the gauge it has been customary to assume that the lower average drainage of the summer months is directly due to a greater amount of evaporation taking place in these months. The results of the present enquiry direct attention to a second possibility, namely that the water content of the gauges differs considerably at different times of the year, and that the high drainage in winter is in part to be ascribed to the accumulation of water during the rainy months of autumn, while the lower drainage in summer is due to the partial depletion of the gauges during the lower rainfall of the spring months. The statistical facts bearing on this point are as follows:

(i) When as in Table III allowance is made for the temperature difference between the different months of the year, the distribution of percolation is little altered on all three gauges.

(ii) The regressions of drainage on temperature are not uniformly or even predominantly negative, as would be the case if the only effect

upon drainage were due to an increase in evaporation. Table VIII shows on the contrary a prevalence in all three gauges of the positive coefficients.

(iii) The discharge from the 60 in. gauge is slightly but significantly delayed in the dates of its annual incidence compared to that of the 20 in. gauge, the 40 in. gauge being in this respect intermediate between the others. This difference can scarcely be ascribed to anything save the greater capacity of the soil in the deeper gauge.

4. The discharge from all three gauges has increased slightly during the period of observation, the increase being greatest in the 60 in., and least in the 20 in. gauge.

5. Both the average drainage and the average response to rain is greatest in the 40 in. gauge; with respect to the other two gauges the mean drainage is slightly higher for the 60 in. gauge, but the average response to rainfall is greater for the 20 in. gauge.

6. Very high and remarkable positive regressions of rainfall on temperature are observed for the months of May and September.

7. During the period of observation the regression of drainage on temperature has tended on the average towards increasing positive values.

8. The residual variations in drainage, not accounted for in terms of current rainfall and temperature, are in all months small compared to the actual values. In March, June and August, however, the standard error of prediction approaches half an inch. This residue could doubtless be further reduced by using a quadratic function of the monthly rainfall. Variation in previous weather, which, as has been shown, is evidently of great importance in comparing different months, can contribute relatively little to the variation among months of the same kind.

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THE APPLICATION OF HEAT OF WETTING MEASUREMENTS TO SOIL RESEARCH PROBLEMS.

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(With Four Text-figures.)

I. Introduction.

The heat of wetting measurement has been introduced into soil science by E. A. Mitscherlich (1), who constructed for his investigations a rather complicated apparatus, consisting of an ice calorimeter which had been adapted for the special requirements of soil tests. Mitscherlich used the heat of wetting as a measurement of the heaviness of different soils, but soon found the technique too difficult, and later preferred the well-known hygroscopicity determination which he had worked out in collaboration with H. Rodewald (2).

The hygroscopicity and the heat of wetting figures show a close correlation, since both of them relate to the same process of liquid adsorption, although they do not measure the same thing. Since the heat of wetting had only been abandoned because of the intricacy of the method, it appeared very desirable to develop another technique, which should combine a sufficient accuracy with the necessary rapidity of determination. The author has taken up this problem and worked out a new method for the determination of the heat of wetting, which satisfies these requirements (3, 4). An English description is given in a Technical Communication (No. 27, 1933) of the Imperial Bureau of Soil Science.

II. The accuracy of the method.

The method differs widely from the one which Mitscherlich used, and it is necessary to investigate whether the alterations are admissable or not.

First of all the drying is different, for Mitscherlich dried his samples over P_2O_5 in a vacuum at 100° C., but although this gives a more intensive drying than an ordinary oven, the soil does not become absolutely dry. This is practically impossible, and it should be recognised that any method for drying soil samples is merely conventional. If the drying temperature is altered, the heat of wetting responds distinctly even to slight alterations, as shown in Table I.

Table I.

	Drying temperature (° C.)			
	105	110		155
	Heat of wetting in cal./gm.			
Soil 1	2·41	2·57		2·87
	2·39	2·50		
		2·57		
		2·53	Av. 2·54	
2	3·20	3·47		4·18
	3·22	3·43		
		3·47		
		3·43	Av. 3·45	
3	4·45	4·63		5·27
	4·43	4·63		
		4·60		
		4·64	Av. 4·62	

In these experiments three different temperatures were used, which were prescribed by the available equipment. The experiments give full evidence for the predominant importance of the drying temperature, and it is quite clear that satisfactory results can only be expected if the drying temperature is carefully kept constant.

Another problem is the duration of drying. It takes some time before an equilibrium is reached between the vapour pressure in the oven and of the soil, and therefore the time of drying must be long enough to be sufficient for all soils. In the experiments recorded in Table II an equilibrium appears to be obtained after 8 hours' drying at 110° C., but exceptionally heavy soils might require longer drying. The temperature

Table II.

	Drying temperature (° C.)							
	105		110				155	
Time of drying ..	16 hr.	36 hr.	4 hr.	8 hr.	16 hr.	40 hr.	23 min.	46 min.
Soil 1	2·41	2·44	—	—	—	—	2·87	2·78
	2·39	2·39						
2	3·20	3·26	3·42	3·46	3·47	3·48	4·18	4·14
	3·22	3·29	3·41	3·46	3·43	3·46		
3	4·45	4·40	4·40	4·59	4·60	4·59	5·27	5·25
	4·43	4·47	4·46	4·68	4·64	4·62		

and time of drying is therefore fixed at 110° C. and 16 hours, which is also a very convenient time, since the drying can then be carried out overnight.

The wetting process is also different in the new method. The soil certainly is more readily wetted if the wetting is done in a vacuum, but this entails considerable experimental difficulties. It is practically impossible to have both wetting under vacuum and thorough stirring. The stirring seems to be more important, since it not only serves to hasten the wetting process, but it also gives a quick equalisation of the temperature after the heat is evolved. This is of particular importance when, instead of an ice calorimeter, an ordinary calorimeter is used, since this is liable to experimental errors which increase with a prolongation of the determination.

III. HEAT EFFECTS RESULTING FROM LIQUID ADSORPTION BY THE SOIL.

The conceptions about the character and the origin of the heat effects measured in the heat of wetting have considerably changed lately. Formerly it was assumed that the soil surface adsorbs the water physically, covering itself with a certain number of molecular layers of water according to the vapour pressure. This conception was supported by measurements of the specific weight, which increases with the heaviness of the soil. Such an increase is certainly due to liquid condensation, but the question is, whether the condensation is caused by polar or non-polar adsorption. If both of them are active in the process of wetting soil, the heat of wetting should be higher with increasing polarity of the liquid. Actually water as a distinctly polar liquid produces a high heat of wetting, whereas a non-polar liquid, for example carbon tetrachloride, gives a smaller one, amounting to only about one-third of the water heat of wetting, where mineral soils are concerned. (The humus content of the soil causes considerable complications which will be dealt with in another section.)

For both polar and non-polar adsorption the effect is similar. The higher the dehydration, the more heat is evolved when the soil is rewetted. If the heat of wetting of samples with different degrees of dehydration is measured, ranging from full saturation to the highest possible dehydration, curves are obtained like those in Fig. 1. In these experiments the samples were first dried all alike, and then a certain quantity of water added by putting a small tube with the water upright into the weighing glass containing the dry sample. The glass was sealed and allowed to stand for a few weeks until the water was evaporated from the tube and adsorbed by the soil or the starch respectively. Later the heat of wetting was determined in the ordinary manner, and the quantity of water added to the dry sample was taken into account.

The curves for the water heat of wetting in Fig. 1 are very similar to those formerly obtained by E. A. Mitscherlich (5). They are quite regular and do not show any break or discontinuity. The distinctly different appearance of the carbon tetrachloride curve points to fundamental differences between the polar and non-polar adsorption, which will be shown more clearly in the experiments described below.

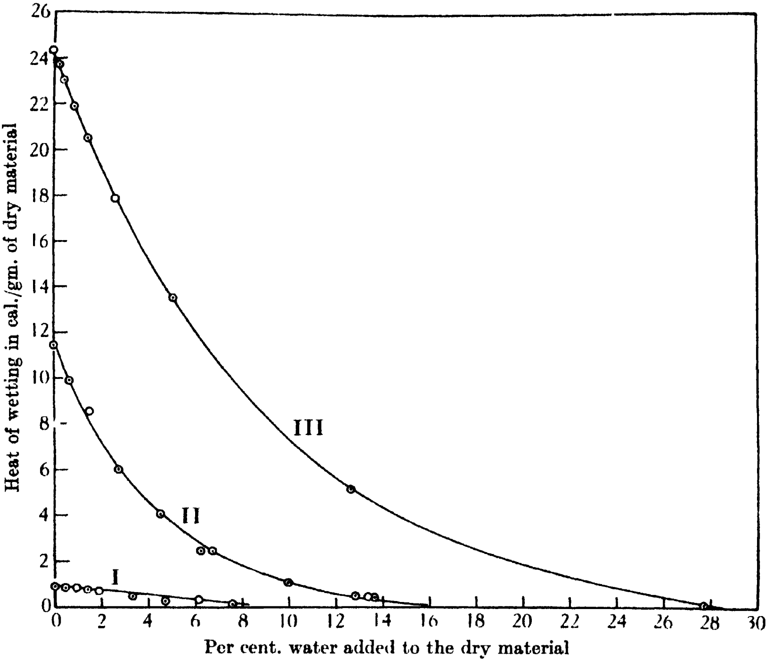

Fig. 1.

I. Brick-clay wetted with carbon tetrachloride. II. Clay wetted with water. III. Starch wetted with water.

The polar adsorption should be closely correlated with the exchangeable bases held by the soil, and consequently there should be some correlation between the heat of hydration of the adsorbed cations and the heat of wetting obtained with a polar liquid. P. Vageler and

F. Alten (6) quote the heat of hydration of the main soil cations as follows:

	H	Na	K	Mg/2	Ca/2
Heat of hydration per milli-equivalent: cation (cal.)	247	94	75	229·5	174·5

These rather theoretical figures are valid for absolutely free ions which are quite inconceivable. The adsorbed cations are not free, but are bound to the alumino-silicate complex. Hence only a certain proportion of the total heat of hydration can reappear, when the dry soil is wetted, and this gives the heat effect that is called the heat of wetting. This proportion, however, must be approximately constant for any soil, if this theory of the origin of the heat of wetting is correct.

Thanks to the kind permission of Mr E. W. Russell to use some of his separated clays, I was able to prove the validity of this theory on a large scale with well-prepared material. The results of these experiments are given in Tables III and IV. The single-base clays had been obtained from hydrogen clay by a prolonged treatment with the acetates and subsequent washing with water or alcohol to remove the acetic acid and salts. Table III shows, besides the heat of wetting, the base-exchange capacity, determined by R. K. Schofield with his new phosphate method (7). The heat of wetting figures obviously follow the base-exchange capacity, and there is a close correlation between the total heat of hydration and the heat of wetting. The relation between these two values can be expressed by the quotient $\frac{\text{heat of hydration}}{\text{heat of wetting}}$, as shown in Table IV. This quotient is constant for all soils, the small variations being due to experimental errors and probably the impurity of the material. This indicates that the heat of wetting must be regarded as a portion of the total heat of hydration of the adsorbed cations. This proportion, however, differs considerably for the various cations, according to the intensity of their adsorptive binding. The adsorption is strongest for hydrogen, and therefore only 1/11·5 of the total heat of hydration is returned in the heat of wetting. Sodium, on the other hand, is but little adsorbed, and consequently a much higher proportion of the heat of hydration, viz. 1/4·9, appears in the heat of wetting. The other cations fall between and follow each other in the well-known order of intensity of adsorptions:

H	>	Mg/2	>	Ca/2	>	K	>	Na
1/11·5		1/9·0		1/7·0		1/5·1		1/4·9

These results are confirmed by the measurements of L. D. Baver (8),

Table III.

Separated clay sample	Base-exchange capacity milliequivalent 100 gm. (R.K.Schofield)	H Heat of		Mg/2 Heat of		Ca/2 Heat of		K Heat of		Na Heat of	
		Wetting cal./gm.	Hydration cal./gm.	Wetting cal./gm.	Hydration cal./gm.	Wetting cal./gm.	Hydration cal./gm.	Wetting cal./gm.	Hydration cal./gm.	Wetting cal./gm.	Hydration cal./gm.
Triassic clay	25	5·36	61·75	6·28	57·38	6·49	43·62	3·76	18·75	4·84	23·50
Barnfield	26	5·44	64·22	—	—	6·08	45·37	3·78	19·50	4·94	24·44
Carse	40	8·61	98·80	—	—	9·96	69·80	—	—	—	—
Rothamsted	41	8·96	101·27	—	—	10·46	71·54	5·80	30·75	7·51	38·54
Lower Lias	42	9·05	103·74	10·71	96·39	10·41	73·29	6·27	31·50	8·08	39·48
Oolite	45	—	—	—	—	11·37	78·52	—	—	9·06	42·30

Table IV.

Separated clay sample	$\frac{\text{Heat of hydration}}{\text{Heat of wetting}}$				
	H	Mg/2	Ca/2	K	Na
Triassic clay	11·5	9·1	6·7	5·0	4·9
Barnfield	11·8	—	7·5	5·2	4·9
Carse	11·5	—	7·0	—	—
Rothamsted	11·3	—	6·8	5·3	5·1
Lower Lias	11·5	9·0	7·0	5·0	4·9
Oolite	—	—	7·0	—	4·7
Average	11·5	9·0	7·0	5·1	4·9

who determined the heat of wetting for several pure single-base clays. Since the base-exchange capacity of these clays is not given in his paper, it has been calculated (Table V) from the figures obtained for the calcium clays, which are probably the most accurate ones. A direct comparison is then possible between the heat of wetting figures determined by L. D. Baver and those calculated from the heat of hydration by using the factors given above.

Table V.

			Heat of wetting	
Soil	Base-exchange capacity calculated	Treatment (cation)	Determined (Baver) cal./gm.	Calculated (Janert) cal./gm.
Toledo silty clay, 0–5 in.	30·1	H	6·50	6·47
		Mg	7·61	7·67
		Ca	7·53	7·53
		K	3·98	4·42
		Na	5·99	5·78
Toledo silty clay, 14–18 in.	25·4	H	5·86	5·46
		Mg	6·99	6·48
		Ca	6·34	6·34
		K	3·74	3·73
		Na	4·31	4·88
Ellsworth silt loam, 17–28 in.	13·6	H	3·63	2·92
		Mg	3·88	3·47
		Ca	3·40	3·40
		K	2·08	2·00
		Na	2·96	2·61
Ellsworth silt loam, 28–30 in.	14·1	H	3·28	3·03
		Mg	3·53	3·59
		Ca	3·53	3·53
		K	2·00	2·07
		Na	2·25	2·71
Clermont silt loam, 0–8 in.	10·2	H	2·44	2·19
		Mg	2·64	2·60
		Ca	2·56	2·56
		K	1·76	1·50
		Na	1·92	1·96

Considering the experimental difficulties and the fact that Baver and the present writer used different methods for their determinations, the agreement is very satisfactory (Table V).

It would be expected that the close correlation between the base-exchange capacity and the heat of wetting, which has been observed for the rather artificial single-base clays, exists also for natural soils. The large differences in the heat of wetting shown by the prepared clays are not likely to appear in natural soils, because there are no pure single-base soils. Generally all the main soil cations are represented in the adsorbing complex, though not in the same proportion, since one or two are usually prevalent and others deficient. This causes alterations in the hydration forces and consequently in the heat of wetting, which can therefore not show a linear correlation with the base-exchange capacity, but only a general correspondence. This is entirely confirmed by experiments carried out with a large variety of soil samples, including salt soils from India, lateritic soils from the Gold Coast and others from South Africa, the Sudan and Palestine, in addition to about a dozen samples from various parts of England. I am very much indebted to Dr R. K. Schofield who did the phosphate tests, the results of which are given in Fig. 2, in relation to the heat of wetting.

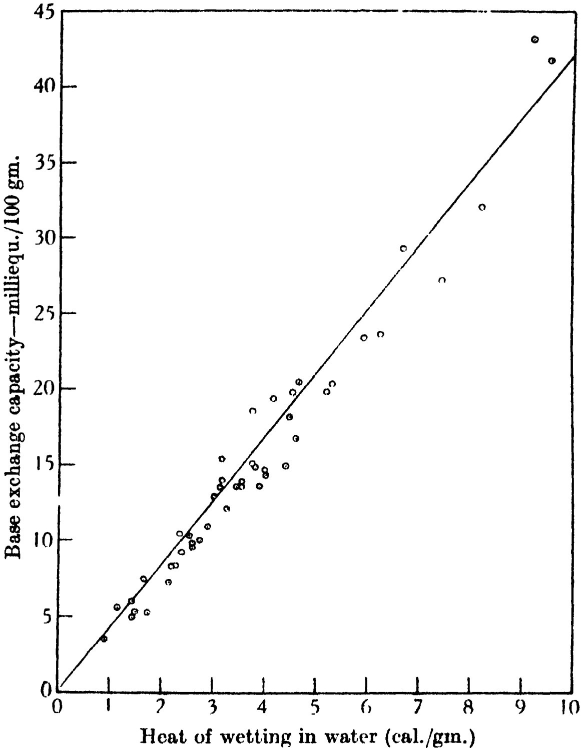

Fig. 2.

Among the adsorbed cations there is generally little sodium and potassium, their adsorption being very weak. If we therefore suppose the remaining cations to be adsorbed on the average in equal amounts, the values for the base-exchange capacity should be theoretically about 4·2 times the heat of wetting figures, as indicated by the straight line in Fig. 2. The results group themselves quite satisfactorily along this line, thus confirming the theory developed above.

Interesting correlations can also be established between the heat of wetting of a soil and its "heaviness" under certain conditions. Since the heaviness of a soil is a very complex conception which has not yet been specifically defined, it cannot be directly measured by any physical method. One of the most direct measurements of the heaviness of a soil is the draw-bar pull exerted by a tractor when ploughing. The heat of wetting of a series of samples taken in the course of measuring the draw-bar pull required to plough Broadbalk Field at Rothamsted was determined, and the results are given in Fig. 3. Although the field measurements and laboratory tests appear to be entirely different, there is quite a good correlation between these two quantities. This is not so surprising, since W. B. Haines and B. A. Keen (9) showed the draw-bar pull was closely correlated with the clay content. These authors found that the draw-bar pull and the ease of drainage were closely correlated, and this is borne out by drainage investigations in Germany (10), which have also shown that the heat of wetting gives a good indication of the ease with which a soil will drain under field conditions.

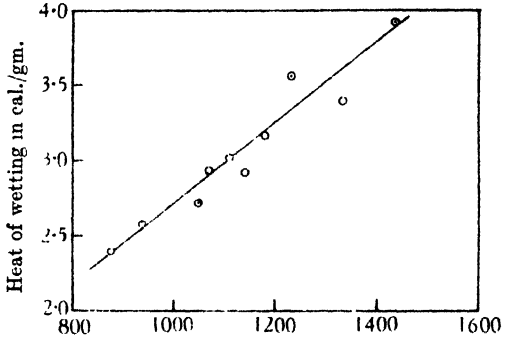

Fig. 3.

IV. THE WETTING WITH ORGANIC LIQUIDS.

The attempt has already been made to use organic liquids for soil physical tests. E. A. Mitscherlich (5) has used in his wetting experiments various organic liquids in comparison with water, and he has found that the heat effects follow in principle the same rules, although they show considerable differences in magnitude. A remarkable exception was, however, encountered when humus soils or starch were tested. These materials gave a very high heat of wetting in water, but only a small heat effect in organic liquids. Mitscherlich concluded from his results that these materials are characterised by a microporous structure, thus developing a so-called "inner" surface, which is easily wetted with water but not with organic liquids, the molecules of which are too big to pass the narrow pores. He proposed to distinguish between an "outer" and an "inner" surface, assuming that the latter can only be wetted by water.

This theory disregards the influence of the polarity of the different liquids, which should be considerable. A detailed study of this question appears very desirable, since it might lead to a better knowledge of the adsorption processes in the soil. The author took up this question and carried out a set of experiments, which were done on soils practically free from humus, in order to avoid disturbances due to organic material. Six samples, as different as possible, were selected, and the heat of wetting determined in water and four organic liquids. The results are given in Fig. 3, where the heat of wetting obtained with the organic liquids is plotted against the water heat of wetting. The non-polar carbon tetrachloride produces the smallest heat effect. The values for paraffin, though also non-polar, lie a little higher, which is probably due to some impurity. The polar liquids, xylene and nitrobenzene, give a much higher heat of wetting, nearing that obtained with water. The latter is, however, still higher, although the dipole moment of water is only $1 \cdot 8 . 10^{-18}$, *i.e.* considerably smaller than the dipole moment of nitrobenzene which is $3 \cdot 9 . 10^{-18}$. This seems to show that the polarity is not the only criterion determining the adsorptive heat effects, but the volume of the molecule plays also a part according to the older conception of Mitscherlich.

Even these two factors do not suffice to explain the comparatively high values for xylene. These should be much smaller than the nitrobenzene figures and only slightly higher than the carbon tetrachloride heat effects. So far no explanation can be given for this discrepancy.

The behaviour of the humus soils which were tested besides the mineral soils given in Fig. 4 was very interesting. The results for the mineral soils fall in a straight line, but any soil containing humus was clearly out of that line, the deviation being obviously determined by the humus content.

If the quotient $\dfrac{\text{water heat of wetting}}{\text{organic liquid heat of wetting}}$ is constant for mineral soils, regularly increasing with progressive humus content, as has been qualitatively observed, it might be possible to work out a rapid method for a quantitative determination of the humus content. This is now being investigated in collaboration with J. L. Russell.

As a preliminary study some Russian soil profiles have been tested and for the different horizons the "humus quotient" was determined, using carbon tetrachloride as organic liquid. These experiments give a rough idea of how the humus quotient may be used in soil science. Its value would of course be much greater if it actually were possible directly to calculate the humus content from it.

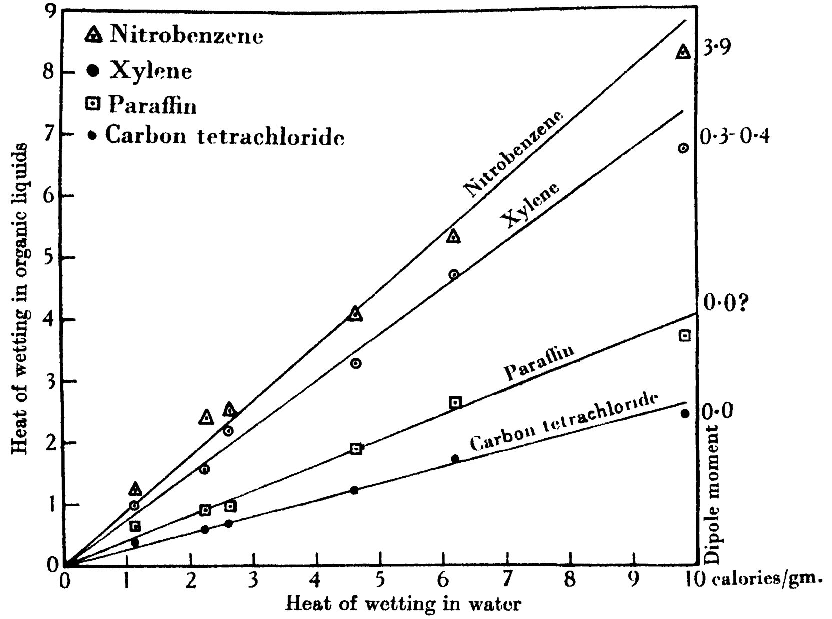

Fig. 4.

The experimental data given in Table VI show the humus quotients for two very different soil types. The highest humus quotient is found in the chernozem, horizon A, decreasing steadily down to horizon C, thus indicating a deep and fertile soil. In the podsol profile the different horizons are most clearly differentiated. The accumulation of humus is restricted to the surface layer, decreasing rapidly from A_1 to A_2. Horizon B_1 is extremely poor, deprived of colloidal material and distinctly less fertile than the underlying subsoil in B_2 and C.

Table VI. *Russian profiles.*

Soil type	Horizon	Identification	Heat of wetting cal./gm. H_2O	Heat of wetting cal./gm. CCl_4	Humus quotient
Podsol	A_1	A. 1297	3·21	0·38	8·45
(Detzkoye Selo)	A_2	A. 1298	1·76	0·37	4·75
	B_1	A. 1299	1·27	0·40	3·18
	B_2	A. 1300	2·30	0·58	3·96
	C	A. 1301	2·65	0·70	3·79
Chernozem	A	A. 1314	8·29	0·65	12·75
(Izberdey)	B	A. 1315	7·21	0·89	8·10
	C	A. 1316	5·32	1·14	4·67

V. AN APPLICATION OF THE METHODS DESCRIBED TO "CLASSICAL FIELDS" AT ROTHAMSTED AND WOBURN.

The classical fields at Rothamsted provide a unique opportunity for investigating the influence of a very prolonged manurial treatment on the physical conditions of the soil. In the case of Broadbalk Field the manuring repeated every year in exactly the same way over a period of nearly a century should distinctly demonstrate an alteration of the physical conditions, if such an alteration is at all caused by the treatment practised on the different plots. Samples were taken from those plots showing the greatest differences in treatment and yield, and these samples were tested by the methods described above. The results are given in Table VII, where the figures of columns 5 and 6 are most important.

The "degree of natural dispersion" quoted in column 5 is determined by a combination of the heat of wetting measurement with a simple elutriation test. The latter serves to determine the proportion of fine particles with a diameter of less than 0·02 mm., which is, however, not identical with the equivalent fraction of the mechanical analysis, since no artificial dispersion is applied in the elutriation. Therefore the percentage of fine particles as determined by elutriation is greatly influenced by the soil structure. For a medium soil the percentage of particles $< 0·02$ mm. is about eight times the heat of wetting expressed in cal./gm. This factor is smaller for soils showing a well-developed crumb structure, but it exceeds 10, and is sometimes even greater than 15 for soils in bad structure. It is therefore successfully used as a measure for the "degree of natural dispersion" of soils (11, 12).

The figures for Broadbalk Field (Table VII, column 5) lie round about 8, but there are differences which are just significant. Plot 2 shows by far the best structure, as was to be expected, since this plot has regularly received farmyard manure. It therefore has also the highest humus quotient (column 6). The worst structure is found on plot 5 receiving minerals only. The other differences do not seem to be significant enough to draw conclusions from them.

Table VII. *Broadbalk Field.*

1 Plot No.	2 Treatment	3 Heat of wetting cal./gm.		4 Particles $<0\cdot02$ mm. %	5 Degree of natural dispersion	6 Humus quotient H_2O/CCl_4, heat of wetting
		In water	In CCl_4			
2	Dung	3·70	0·62	17·7	4·8	6·0
3	Unmanured	2·50	0·73	20·2	8·1	3·4
5	Complete minerals	2·39	0·70	20·8	8·7	3·4
6	Minerals + 206 lb. N	2·52	0·68	20·6	8·2	3·7
7	Minerals + 412 lb. N	2·95	0·73	21·6	7·3	4·0
8	Minerals + 618 lb. N	2·96	0·66	18·2	6·1	4·5
9	Minerals + 275 lb. nitrate of soda	2·64	0·61	20·9	7·9	4·3

N means in this table "sulphate of ammonia."

The humus quotient (column 6) is only 3·4 on the unmanured plot and the same on No. 5 with complete minerals. These plots are both very poor in humus, but the humus content goes up with increasing nitrogen dressings (plots 6, 7, 8), as is clearly shown by the humus quotient.

On the whole, the differences observed on Broadbalk are very small, considering the permanency of the treatment. The heavy soil of Broadbalk resists very well the influences of the one-sided treatment, and the reserves of such a soil will probably prevent much greater changes in structure for some long time to come. The effect should be quite different on a light soil, and it is very fortunate that similar experiments could

Table VIII.

1 Plot No.	2 Treatment	3 Heat of wetting cal./gm.		4 Particles $<0\cdot02$ mm. %	5 Degree of natural dispersion	6 Humus quotient H_2O/CCl_4, heat of wetting
		In water	In CCl_4			
31	Sulphate of ammonia alone	1·42	0·36	14·3	10·1	3·9
32	Sulphate of ammonia + minerals	1·47	0·40	13·4	9·1	3·7
33	Sulphate of ammonia + lime	1·56	0·39	8·0	5·1	4·0
34	No manure	1·37	0·36	6·8	5·0	3·8
35	Nitrate of soda	1·52	0·36	8·7	5·7	4·2

be repeated on the light Woburn soil, where some of the permanent barley plots provided the material for the laboratory tests, the results of which are shown in Table VIII.

Although the Woburn field experiments were laid out much later than those on Broadbalk Field, there is already a very marked effect of the manuring on the physical condition of the soil, particularly its structure. The soil structure is very good on the unmanured plot with a degree of natural dispersion of 5·1, but there is an enormous deterioration on the plots receiving sulphate of ammonia. Here the degree of natural dispersion is 9·1 and even 10·1, *i.e.* a doubling of the natural dispersion. The plot which receives lime in addition to sulphate of ammonia is, however, normal. This shows that it is only the calcium which is already exhausted by continuous physiologically acid manuring in this light soil. The nitrate of soda, on the other hand, has only produced a small change of the natural dispersion, which is in accordance with field observations.

The humus quotient shows practically no change on the few plots that were tested. Apparently there is little accumulation of humus in this light dry soil.

We may conclude from these experiments that certain changes of the physical conditions in the soil on the permanent experimental fields at Rothamsted and Woburn have been clearly distinguished by the new methods applied.

VI. CONCLUSIONS.

1. Experiments carried out with pure single-base clays have shown that the heat of wetting represents a specific proportion of the heat of hydration of the adsorbed cations in their free state.
2. Correlations exist between the heat of wetting and various other soil properties determined in the field or by laboratory methods.
3. Wetting with organic liquids produces a heat effect which is proportional to the water heat of wetting for mineral soils. The dipole moment and the molecular volume of a liquid do not seem to determine completely the heat of wetting of a given soil in it.
4. New methods were applied to some of the permanent plots at Rothamsted and Woburn, where changes in the physical condition of the soil could be distinguished.

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ON THE COMPOSITION OF COMMON HEATHER (*CALLUNA VULGARIS*).

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INTRODUCTION.

THE economic importance of the common heather or ling (*Calluna vulgaris*) is little appreciated by those not intimately concerned with the preservation of game, or the management of hill sheep, and investigators have given scant attention to its composition and feeding value. Yet it is the staple food of the grouse and, in many districts, contributes largely to the diet of the Blackface sheep. The young and tender shoots are eaten at all seasons of the year, but are of special value in winter, for heather is evergreen and withstands the action of frost in normal years. Further, its habit of growth is such that sheep may obtain access to it during snowy weather.

In 1884 Wallace and Kinch (1) published analyses of heather and other moorland plants and stated that, to their knowledge, the composition of such of these plants as have been found by experience to be valuable to sheep, had not previously been determined. It does not appear that any data relative to the composition of heather has been published since, although some analyses have been made by Godden (2) at Aberdeen, and by Fagan (3) at Aberystwyth.

The subject of heather burning has given rise to much controversy; while the practice is indisputably valuable for the maintenance and improvement of sheep grazing, it has been discountenanced by many shooting tenants and gamekeepers. These conflicting interests would now seem to be almost reconciled, and it is generally recognised that burning is good for both sheep and grouse. Heather of any considerable age is undesirable for a number of reasons. It debars sheep from a free range, as they are not inclined to go through it. It occasions wastage of wool and, as much of the loss is from the underpart of the body, sheep tend to suffer in health. Young grouse get lost in it, or may be hanged by the long stems. Further, the plant loses vitality and grows more slowly with age, so that the longer burning is deferred the more difficult does re-establishment become. The new shoots are long in appearing and few in number; if hard grazed the plant dies out, and bracken infestation may follow. So much is known from the experience of practical men. It is also claimed that the digestibility and feeding value of heather declines with age, although this does not seem to have been precisely demonstrated. The object of the present investigation was to determine whether the edible portions of heather are subject to such changes, and the nature of them.

EXPERIMENTAL.

Samples were obtained from the farm of Newbiggin, near Blanchland in Northumberland. The hill grazing on this farm is largely heather moor and, having been well managed and regularly burnt, includes heather of age varying from 1 to 10 years. Only a small acreage of aged heather existed at the time of sampling. The land may be described as "dry moor," shallow peat overlying a sandy clay. The underlying rock is a sandstone of the Millstone Grit Series.

Strips of heather known to have been burnt 2, 4, 6 and 8 years previously were selected, and samples obtained in each case by bulking random cuttings taken within a radius of 12 yards from a central marking post. A sample was also obtained from an area which had not been burned for at least 20 years.

As the determination of dry-matter content was not considered likely to yield useful results, the samples were neither weighed when cut nor packed in airtight containers, but conveyed to the laboratory in seed bags. That portion of leaf and stem which was estimated to be of the current season's growth, and would include most of the material eaten by sheep, was separated from one half of each sample. From the other half an attempt was made to separate the growth of seasons 1931 and 1932. It was thought that this fraction might prove of interest, as the grouse does not appear to feed exclusively on the most recent growth, a considerable amount of woody material of 2 or 3 years' growth being sometimes found in the crop. The hand picking involved in the preparation of samples for analysis proved very laborious.

For the *in vitro* determination of digestibility of crude protein the pepsin-hydrochloric acid method circulated by the Agricultural Education Association (4) was employed. The time of digestion was 12 hours, and it is obvious that the percentage digestibility figures shown in Table I are too low, although their usefulness for purposes of comparison is probably undiminished. True protein was determined by the Stutzer process, and other constituents by the usual analytical methods. Two-gram samples for the determination of moisture were always weighed simultaneously with portions required for other determinations. The moisture content was calculated on one weighing after an arbitrary drying period of 24 hours in an electric oven at 100° C.

The analytical results are shown in Table I. It will be noted that, for purposes of comparison, the analysis of grass samples from plots 6 and 4 of Tree Field, Cockle Park, are appended. The former plot has received no treatment of any kind since 1897, and the latter has been dressing with 5 cwt. of basic slag every third year during the same period. Both of the grass samples were cut on the same day as the heather, the cutting areas having been cleared exactly 28 days previously.

Table I. *Percentage of soil-free dry matter.*

Age ...	2 years	4 years		6 years		8 years		Aged		Tree Field, Cockle Park	
	A	A	B	A	B	A	B	A	B	plot 6	plot 4
*Crude protein	11·89	8·56	7·69	7·39	7·25	6·95	6·51	6·91	6·38	12·49	16·96
Ether extract	3·06	4·30	3·91	4·65	3·87	5·05	4·17	5·25	4·05	1·73	2·47
Fibre	22·21	21·67	23·00	21·49	21·46	20·42	22·11	21·12	24·82	24·39	22·65
†Ash	4·51	3·26	3·23	3·72	3·62	3·08	3·04	3·14	3·04	4·73	6·77
*Including											
True protein	11·55	8·41	7·62	7·23	7·11	6·65	6·40	6·72	6·29	11·44	15·23
Amide nitrogen	0·081	0·085	0·061	0·073	0·047	0·045	0·060	0·051	0·059	0·099	0·121
Ammoniacal nitrogen	0·059	0·045	0·042	0·047	0·044	0·041	0·043	0·047	0·037	0·056	0·064
†Including											
Phosphoric acid (P_2O_5)	0·492	0·216	0·179	0·257	0·243	0·216	0·199	0·227	0·197	0·358	0·917
Lime (CaO)	0·918	0·470	0·438	0·604	0·615	0·554	0·850	0·694	0·558	0·625	1·008
Percentage solubility of crude protein in pepsin-HCl solution at 38° C.	30·37	25·00	15·22	21·65	17·69	14·69	12·33	14·89	10·66	35·23	46·23

A, growth made in 1932; B, estimated growth of 1932 and 1933.

DISCUSSION.

It would appear from the figures tabulated above that the crude protein content of growth made during 1932 declines consistently as the plant ages, although the extent of fall is not so great as had been anticipated. The highest protein found, viz. that appertaining to the foliage of 2 years old heather, is even less than that in the very poor grass of plot 6, Tree Field. The percentage of crude protein in material of two seasons' growth (1931 and 1932) shows a similarly consistent decline with age, and is in every case less than in the 1932 growth of heather of like age.

A very high percentage of the total nitrogen in all samples is present as true protein, and the small difference is almost wholly accounted for as ammoniacal and amide nitrogen. These last two constituents show little variation, and are not present in large enough amount to be of interest.

The digestibility of the crude protein, as measured by the pepsin-hydrochloric acid method, is comparatively low even in the youngest heather. It has been already indicated, however, that the period of digestion used was too short to give values comparable with those obtained *in vivo*. There is a marked and consistent decline as the plant ages. As was to be anticipated, the digestibility of 2 years' growth is always substantially less than that of the 1932 growth on heather of corresponding age.

The fibre content does not differ appreciably from that of pasture grass, and bears no obvious relationship to the age of the plant. There is a steady and probably significant increase in ether extract with age, and the figures are always higher than in pasture grass.

There is no evidence that the percentage of total ash declines in heather of more than 4 years of age. While the phosphoric acid and lime figures relating to 2 years old heather are high, variation in the older samples does not appear to be significant, and there is no evidence of an age effect.

Working on heather of varying age obtained from the Isle of Jura, Godden (2) obtained results which agree with those given in Table I in certain particulars only. The maximum crude protein content was found in the sample aged 4 years, thereafter a consistent decline with age is recorded. The percentages of ether extract found were markedly higher than in the present investigation, 2 years old heather containing over 10 per cent. in the dry matter. Old samples contained between 8 and 9 per cent. with no evidence of significant variation. Lime and phosphoric acid both showed a consistent decline with age.

The samples examined by Kinch (1) and by Fagan (3) appear to have consisted of one season's growth, but the age of the plants from which they were obtained is not stated. The total crude protein content is, in both cases, over 9 per cent., and in other respects the composition is consistent with samples taken from plants of 4 or 5 years of age. It is noteworthy that the dry matter of Fagan's sample contained no less than 1·07 per cent. of lime (CaO).

It should be emphasised that the investigation described was of a preliminary character, and that the results obtained will admit only of tentative conclusions which, in any event, cannot be justly applied to heather grown under different conditions of soil and climate. The separation of growth of known age from large samples proved to be difficult, and the use of single sampling areas was doubtless productive of some errors.

Further work with the object of determining the effects of season and other factors has been undertaken, and is now in progress.

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THE FERTILISING VALUE AND NITRIFIABILITY OF HUMIC MATERIALS PREPARED FROM COAL.

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(With Three Text-figures.)

LITTLE is known about the direct or indirect effects of the highly decomposed organic matter of the soil—the humic matter—on the nutrition and growth of cultivated crops. When present in considerable amounts it improves the physical properties of the soil by giving a better crumb structure and by increasing the water-holding capacity; its colloidal properties may influence the retention and availability of plant nutrients. The frequent use of heavy dressings of dung effects an improvement in soil fertility which is perceptible for many years, over fifty in the barley experiments at Rothamsted, and it is common knowledge among farmers and market gardeners that the fertility, especially of light land, falls off unless steps are taken to maintain the supply of soil organic matter. The materials available, crop residues and animal manures, are not inert sources of humic material. They also contain plant nutrients and readily oxidisable compounds which may profoundly modify the activities of the soil micro-organisms. It is almost impossible in such mixtures to assess the relative importance of the several components. Direct experiments on the addition of humic matter have rarely been attempted on account of the difficulty of preparing sufficient amounts of suitable material; indirect experiments(1) on the removal of humic matter necessarily cause profound changes in the composition of the soil.

The addition of peat has uncertain effects, at any rate in amounts suitable for ordinary arable soils, though it may have value for certain branches of horticulture. But peat cannot be regarded as providing a material akin to the humic matter of soil, for the peat necessarily remains in isolated lumps which become disseminated through the soil extremely slowly. Just as lumps of mineral phosphate are almost useless whereas superphosphate or very finely ground mineral phosphate may be useful as sources of available phosphorus in the soil, so materials which are expected to add directly to the humic matter of the soil should be tested in the form either of very fine powders or as soluble salts. In recording negative results with a series of commerical humic materials, derived from brown coal or peat, O. Lemmermann (2) mentioned that some promising but inconclusive results were obtained in field trials with an ammonium humate prepared from a peat extract. The preparation was however much too expensive to justify any commercial development which would allow tests on an adequate scale.

The desire to discover new outlets for coals of low industrial value has led to much discussion in the technical press of Central Europe on the possible value of brown coal and of certain humic materials prepared by the gentle oxidation of coal. It is possible to produce humic acids which give readily soluble ammonium or potassium salts, and it would appear that such products are more suitable for direct tests on the possible fertiliser value of humic materials than any of the cruder materials previously available. It has been claimed that there is already sufficient evidence to show that manuring with coal will become important in the near future. Unfortunately it would appear that many of the experiments have been made by workers who are more familiar with coal technology than with agricultural experimentation or soil chemistry. The statement of results sometimes suggests propaganda rather than research, and the discussions of the possible mechanism of the crop increases observed are unconvincing. They mention among others the stimulation of the growth of *Lemna* in water cultures, the improvement in physical properties, the direct assimilation of carbon compounds by plants, and the steady liberation of carbon dioxide and available nitrogen (3). Apart however from the hypothetical stimulation of crop growth there is the possibility that a humic acid from coal might provide a suitable carrier for ammonia with certain advantages over ammonium sulphate or might be used with advantage as a drier in mixing compound fertilisers.

With the co-operation of A. Boake, Roberts & Co. Ltd., Stratford, E. 15 and The Powell Duffryn Steam Coal Company, Ltd., Cardiff, it has been possible to carry out a series of experiments in the field, the pot-culture house and the laboratory on humic acids (and their ammonium and potassium salts) prepared from finely ground coal by oxidation with nitric acid at 100° C. in a process in which the excess oxides of nitrogen are recovered for re-use (4). The results showed that the ammonium in ammonium humate was as efficient as that in ammonium sulphate, and there was some indication that the humic material also supplied a small amount of available nitrogen. There was no evidence of any stimulation or other beneficial effect apart from the production of ammonia and nitrate.

In any nitrogenous manure it is clearly essential to ascertain and allow for the availability of the nitrogen before proceeding to examine other effects. The experiments were therefore planned in such a way as to compare the availability of the nitrogen as determined by chemical analysis with the effects of the manures on the yield of the experimental crop. The fact that good correlations were obtained not merely disposes of hypothetical stimulations under the conditions of these experiments but shows that the laboratory technique for determining the availability of the nitrogen in the manure was adequate for its purpose.

The terms "Humic Acid" and "Ammonium Humate" will be used throughout this paper for convenience without, of course, implying that they are regarded as identical with materials present in or extractable from soils.

THE HUMIC MATERIALS.

The humic acid materials were dry fine grey-brown powders, and the ammonium humates were black coarse powders with bright surfaces. Some of the ammonium humates (*e.g.* the material *B* below) dissolved readily and completely in water to give stable dark brown solutions

Table I. *Percentage composition of the humic materials.*

		Dry matter	Ammonia N	Organic N	Total N	Ash	P_2O_5	K_2O
1930 samples:								
Humic acid	*E* 1*	93·2	0·13	4·38	4·51	3·04	0·002	0·044
Ammonium humate	*F* 1*	93·8	3·55	5·86	9·41	3·69	0·007	0·107
,, ,,	*F* 2	88·1	3·21	5·80	9·01	—	—	—
Potassium humate	*G* 1*	85·1	—	3·36	3·36	—	—	16·3

		Ammonia N	Organic N	Total N
1932 samples:				
Humic acid	*A* 1*	—	4·43	4·43
,, ,,	*A* 2	—	4·29	4·29
,, ,,	*A* 3	—	4·24	4·24
Ammonium humate (prepared from humic acid *A*)	*B* 1*	3·16	5·14	8·30
	B 2	3·02	5·14	8·16
	B 3	2·87	5·13	8·00
	B 4	2·76	5·27	8·03
	B 5	2·88	5·07	7·95
Humic acid	*C* 1		3·82	3·82
Ammonium humate (prepared from humic acid *C*)	*D* 1*	1·24	4·72	5·96

* **Materials used in flask and pot experiments.**

similar in appearance and general properties to alkaline humus extracts from soils. All of the humic materials used were prepared by the two firms mentioned. Several batches were used throughout the experiments, but it will be seen from Table I that the different preparations from the same initial materials remained substantially constant in composition. Humic acid *A* in 1932 and humic acid *E* in 1930 were from similar coals; humic acid *C* in 1932 was made from a different type of coal and its ammonium salt (*D*) contained much less ammonia than those (*B* and *F*) derived from the more normal materials. It will be noted that the humic materials contain much more nitrogen than normal coals and further that in the conversion of humic acid into ammonium humate the amount of organic nitrogen increases. A considerable fraction of the nitrogen used as catalyst in the oxidation of coal enters the humic acid. Some of the ammonia used to make the ammonium humate is combined as a product incapable of giving off ammonia on boiling with magnesia according to the methods of analysis laid down in the Regulations of the Fertiliser and Feeding Stuffs Act. In assessing the possible commercial value of such materials it must therefore be remembered that a considerable fraction of the organic nitrogen is derived from inorganic sources in the course of manufacture and that such nitrogen cannot therefore be produced more cheaply than that in the standard nitrogenous fertilisers. Before it is possible to assess any special properties of these materials it is essential to compare them against simple forms of nitrogen on the basis, first, of equal ammonia contents and, second, of equivalent total nitrogen contents. It is clearly recognised that organic materials may through their slower rate of decomposition and through indirect effects on the physical properties and microflora of the soil have effects which operate so slowly that they may be missed in short-period tests in laboratory, pot culture, or field experiments, but new nitrogenous fertilisers must be judged primarily by their immediate effect and, in any case, these immediate effects must be understood before satisfactory long-range experiments can be devised.

The experiments in the present paper were planned to secure as wide a range of experimental conditions as was possible in the course of a single season. A preliminary series of laboratory and pot-culture experiments was carried out in 1930 on a single type of soil. In 1932 similar experiments were made on four contrasting soil types and a series of field trials was conducted on several crops at a number of centres.

LABORATORY AND POT-CULTURE EXPERIMENTS, 1929.

The soil was taken from the side of Broadbalk Field, Rothamsted, but proved to be fundamentally different from the soil of the adjoining permanent wheat plots in that it was devoid of calcium carbonate. It was acid and, in addition, rich not only in nitrate but in readily nitrifiable material. Mustard sown in pots containing 10 kg. of soil on June 27th and thinned to three plants per pot was harvested on August 16th. There were eight treatments in quadruplicate. A basal dressing supplied potassium and phosphorus, the former being adjusted to allow for that in the potassium humate. The organic materials were used at the rate of 0·4 gm. of added total nitrogen per pot which corresponded with 0·15 gm. of nitrogen per pot as ammonia for the ammonium humate. Other pots therefore received 0, 0·15 and 0·40 gm. of nitrogen as ammonium sulphate. Soluble humates and insoluble humic acid were compared by the pairs (*a*) potassium humate and humic acid (both with and without added ammonium sulphate), (*b*) ammonium humate with humic acid and ammonium sulphate. The data in Table II show that the response of the mustard to ammonium sulphate was sufficient to provide a satisfactory range for testing different amounts of available nitrogen. The yield responses to humic acid (4 per cent. without and 5 per cent. with added ammonium sulphate) and to potassium humate (12 per cent. without and 2 per cent. with added ammonium sulphate), though consistently positive are too small to be regarded as significant individually, as is also the slight superiority of the ammonium humate over ammonium sulphate supplying equal ammonia. The experiment suggests but fails to establish a slight benefit from the humic materials as a whole, but it is clear that the immediate effect of an ammonium humate fertiliser must be ascribed to its ammonia rather than to its organic nitrogen or to any secondary effects of the humic material. Humic acid proved at least as efficient as sulphuric acid as an ammonia carrier.

The laboratory nitrification experiments were made simultaneously with the same soil and the same rates of addition of nitrogen (15 and 40 mg. per kg. soil). Large duplicate flasks were set up for each treatment and kept well aerated by frequent shaking. Analyses for ammonia and nitrate nitrogen were made after suitable intervals. The agreement between duplicate flasks was not sufficient to make it possible to detect small differences in response to treatment, but the results are in general agreement with those of the pot cultures. About 90 per cent. of the ammonium sulphate nitrified and only about a third of the organic nitrogen.

Table II.

Treatment	Un-treated	Humic acid *E*	Potassium humate *G*	Ammonium sulphate	Ammonium sulphate + humic acid *E*	Ammonium sulphate + potassium humate *G*	Am-monium humate *F*	Ammonium sulphate	Standard error
N added in gm. per pot with 10 kg. soil:									
As ammonia N	—	—	—	0·15	0·15	0·15	0·15	0·40	—
As organic N	—	0·4	0·4	—	0·25	0·25	0·25	—	—
As total N	—	0·4	0·4	0·15	0·40	0·40	0·40	0·40	—
Pot experiments:									
Mustard, dry matter in gm. per pot	14·6	15·1	16·1	18·4	19·0	18·6	18·8	21·1	0·68
Percentage increase over untreated pot	—	4	12	26	31	28	29	46	6·6
Flask experiments:									
Ammonia N in mg. per kg. soil after days:									
1	10	9	10	—	20	—	19	43	—
21	2	3	3	—	5	—	4	12	—
49	2	1	1	—	2	—	2	4	—
Nitrate N in mg. per kg. soil after days:									
1	33	31	34	—	32	—	32	33	—
7	55	55	54	—	53	—	55	56	—
14	62	58	60	—	62	—	67	74	—
21	67	57	59	—	65	—	66	79	—
49	68	66	71	—	69	—	74	94	—

It will be noted that although nitrification was relatively slow in this experiment and much ammonia remained from ammonium sulphate even after three weeks, yet there was no evidence of any accumulation of ammonia from the humic materials.

LABORATORY EXPERIMENTS, 1932.

The 1932 experiments tested two humic acids and their ammonium humates on four soil types selected so as to give as wide a range of conditions as possible.

Table III. *Mechanical analyses of soils from pot-culture and flask experiments* 1932. *Weights of oven-dry fractions as percentages of air-dry soil.*

	Soil			
	R.	S.	T.	W.
Coarse sand	20·3	33·7	58·5	50·1
Fine sand	37·9	28·4	28·6	29·1
Silt	22·5	10·2	5·3	7·5
Clay	15·0	21·5	5·5	10·0
Carbonates	0·0	0·9	0·0	0·0
Moisture	2·2	2·5	0·6	1·1
Loss on solution	1·0	0·8	0·4	0·5
Difference of sum from 100	1·1	2·0	1·1	1·7
Loss on ignition	5·3	4·6	1·0	3·0
*p*H	5·0	7·4	5·0	5·8

The four soils, whose mechanical analyses of the soils are given in Table III, were:

R. (Rothamsted). As in the 1930 experiments, the soil was taken from the side of Broadbalk Field. It was an acid heavy loam probably containing organic matter remaining from the time some decades ago when the broad headlands of the field were kept under grass.

S. (Saxmundham). A calcareous clay loam from calcareous boulder clay at the Saxmundham Experimental Station, E. Suffolk.

T. (Tunstall). A light acid sand from the Tunstall Experimental Station, E. Suffolk.

W. (Woburn). A slightly acid sandy loam from drift on Lower Greensand at the Woburn Experimental Farm, Beds.

The conditions of the nitrification experiments were standardised much more rigidly than in the preliminary 1930 series. 50 gm. lots of air-dry soil were set up in 350 c.c. conical flasks with the appropriate amount of humic material or ammonium sulphate to give 15 or 40 mg.

of added total nitrogen per kilogram of soil in the series of treatments given in Table IV.

Table IV.

Material added	Nitrogen added in mg. per kg. soil As ammonia	Organic	Total
(1) None	0	0	0
(2) Humic acid *A*	0	40	40
(3) Ammonium humate *D* (prepared from humic acid *C*)	8	32	40
(4) Ammonium sulphate	15	0	15
(5) Ammonium humate *B* (prepared from humic acid *A*)	15	25	40
(6) Ammonium sulphate + humic acid *A*	15	25	40
(7) Ammonium sulphate	40	0	40

Each of the seven treatments was given to six independent flasks for each soil and one flask was taken for analysis after 2, 4, 6, 8, 17 or 26 weeks. The soils were brought to about optimal water content, all of the flasks of one soil receiving equal measured amounts, and the flasks were loosely plugged with cotton-wool and kept in a cellar with little fluctuation of temperature. The flasks were aerated by vigorous shaking every few days and adjusted to constant weight every week by the replacement of the water lost by evaporation. Except in the Saxmundham soil, a satisfactory crumb condition was maintained throughout the experiment. Unfortunately the soils were allowed to become too dry shortly before the analysis at 17 weeks, and the relatively large amount of water added was not uniformly distributed before analysis. This caused an unusual irregularity in the results at this time and also caused the heavy Saxmundham soil in one of the last lot of flasks to gather together into large balls.

After the appropriate period of incubation one flask for each soil and each treatment was analysed for ammonia and nitrate by Carsten Olsen's method (5). The whole of the soil was shaken for 1 hour with *N* KCl containing enough HCl to give a final *p*H of about 1·0. After filtering an aliquot part was distilled with magnesia and then with Devarda's alloy. The initial ammonium and nitrate contents of the soils as set out in Table III were obtained from analyses on the untreated soils, together with the amounts of ammonia added in the various treatments.

This technique has the advantage that it eliminates sampling errors other than those involved in setting up the flasks. Every analytical result is independent of and strictly comparable with every other one.

The data include all of the irregularities and errors not merely of the initial sampling and of the analysis but also of the growth and activities of the micro-organisms throughout the whole experiment. The separate flask technique is greatly to be preferred to that used in the preliminary 1930 series and in much older work in which a few large samples of soil were set up and small samples drawn at the required intervals. Evidence has often been obtained in these laboratories to show that aeration and other irregularities introduced by sampling from a mass of soil may seriously disturb the course of the microbiological activity and the amounts of ammonia and nitrate accumulated.

There are of course no independent replicates, but there can be little objection to taking a high order interaction between treatment, time, and soil as an estimate of error. The following analyses of variance for total inorganic nitrogen in mg. per kg. soil for the periods 2, 4, 6, 8 weeks and for 2, 4, 6, 8, 17, 26 weeks show that the error so estimated is satisfactorily low, especially in the earlier periods before the moisture irregularity already mentioned.

	Period, 2, 4, 6, 8 weeks		Period, 2, 4, 6, 8, 17, 26 weeks	
	Degrees of freedom	Sum of squares	Degrees of freedom	Sum of squares
Soils	3	63,843	3	126,638
Treatment	6	13,836	6	19,857
Time	3	626	5	4,653
Interactions:				
Soils × time	9	1,071	15	6,394
Soils × treatment	18	119	18	296
Time × treatment	18	108	30	410
Soils × time × treatment	54	181	90	735
Total	111	79,783	167	158,982
Standard error per flask		1·83		2·86
General mean		42·6		45·0
Standard error per flask as percentage of mean		4·3		6·4

This analysis of variance shows that the differences between soils, between treatments and for different times are all highly significant. The first-order interactions between these factors taken in pairs are of much smaller magnitude. The interaction of soils and time is definitely significant or, in other words, some soils accumulate inorganic nitrogen more rapidly than other soils, quite irrespective of fertiliser treatment. The nature of this effect is shown in Figs. 1*a* and 1*b* (for the analyses at 2, 4, 6 and 8 weeks), from which it will be seen that when the treatments are averaged there is a great and steady accumulation of nitrate and a slow loss of ammonia from the Rothamsted soil and similar but much smaller effects in the Tunstall soil. Both of these soils are appreciably acid. In the other two soils the ammonia disappears more rapidly and the total inorganic nitrogen remains substantially constant. When fertiliser treatments are considered as a whole their interaction with soils is quite small and only on the verge of significance, whilst that with time is significant.

Table V gives the inorganic nitrogen contents for the seven fertiliser treatments at each time of analysis, averaging the four soils, and the mean recovery of added nitrogen (excess for treated over untreated soil) for each of the soils, averaging the analyses from 2 to 26 weeks. Fig 1*c* gives the mean recovery of added nitrogen for the analyses at 2, 4, 6, 8 weeks, averaging the four soils. It will be noted that there is a slight progressive accumulation of inorganic nitrogen from humic acid *A* and from ammonium humate *D*. The progressive accumulation of inorganic nitrogen from humic acid *A* varies from soil to soil, and this effect accounts for much of the observed interaction between soils and treatment and between time and treatments. It is examined in more detail below. With these minor qualifications the relative unimportance of soil and time effects shows that the nitrifiabilities of the six fertiliser materials may safely be expressed by the mean inorganic nitrogen productions, averaging all time of analysis and all soils. Conclusions from the means of four soils, all showing similar effects, are clearly of more general value

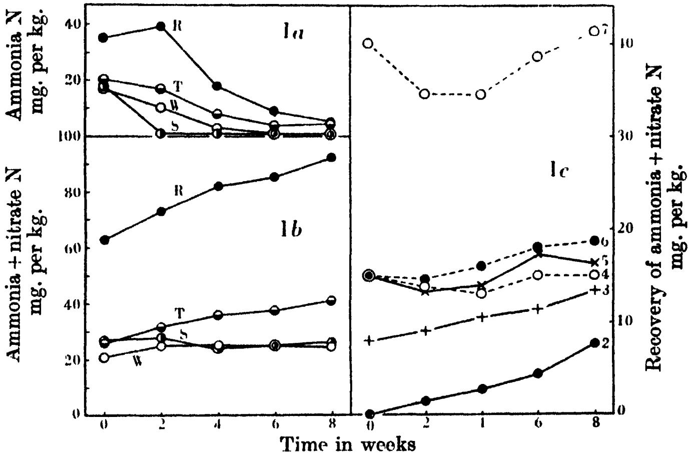

Fig. 1. Nitrification experiments on four soils. Treatments and soils as in Table V. *a*. Ammonia contents of four soils (averaging seven fertiliser treatments). *b*. Ammonia + nitrate contents of four soils (averaging seven fertiliser treatments). *c*. Mean recovery of ammonia + nitrate for seven fertiliser treatments (averaging four soils).

Table V. *Ammonia and nitrate accumulation in incubated soils. All results as mg. of* N *per kg. soil (parts* N *per million).*

Treatment	1 None	2 Humic acid *A*	3 Ammonium humate *D*	4 Ammonium sulphate	5 Ammonium humate *B*	6 Ammonium sulphate + humic acid *A*	7 Ammonium sulphate
Ammonia N added	—	—	8	15	15	15	40
Total N added	—	40	40	15	40	40	40
N found as $NH_3 + NO_3$ (averaging 4 soils) (standard error = 1·43):							
Initially	21	21	29	36	36	36	61
After 2 weeks	27	29	35	41	40	42	62
4	29	32	38	42	44	45	63
6	28	33	39	44	46	46	67
8	30	38	42	45	46	49	72
17	31	33	34	45	46	52	66
26	42	48	54	54	58	59	75
Recovery of added N as $NH_3 + NO_3$ (averaging six times of analysis for 2 to 26 weeks) (standard error = 1·65):							
(*a*) Excess over untreated soil:							
Rothamsted soil	—	6	12	15	18	21	40
Saxmundham soil	—	6	10	14	14	18	33
Tunstall soil	—	2	7	14	16	16	35
Woburn soil	—	2	8	13	14	15	38
(*b*) Excess over soil with 15 mg. N as ammonium sulphate:							
Rothamsted soil	—	—	—	—	4	6	25
Saxmundham soil	—	—	—	—	0	4	19
Tunstall soil	—	—	—	—	3	2	21
Woburn soil	—	—	—	—	0	2	24

than those which would have been obtained if a similar number of analyses had been devoted to replicated tests on a single soil. The similarity of the results in four soils also suggests that nitrate accumulation depends on the availability of the original materials rather than on secondary effects dependent on hypothetical stimulations or on improvements in physical conditions. The mean recoveries of inorganic nitrogen from the added materials are given in Table VI.

Table VI. *Recovery of inorganic nitrogen (in mg. per kg. soil).*

Treatment	Ammonia N added	Total N added	Inorganic N recovered (mean for 2–26 weeks and for 4 soils)
(2) Humic acid *A*	0·0	40·0	4·1
(3) Ammonium humate *D*	8·4	40·0	9·0
(4) Ammonium sulphate	15·2	15·2	13·9
(5) Ammonium humate *B*	15·2	40·0	15·5
(6) Ammonium sulphate + humic acid *A*	15·2	40·0	17·4
(7) Ammonium sulphate	40·0	40·0	36·2
Standard error	—	—	0·82

The initial ammonium content is clearly the primary factor in determining the amount of nitrate formed from the fertilisers. Only small and insignificant amounts of the organic nitrogen of the ammonium humates were nitrified, but there was a small but definite accumulation of nitrate from the humic acid both in the presence and in the absence of added ammonium sulphate. By averaging the two humic acid series (neglecting the difference in the amounts taken for treatments 2 and 6) the nitrification of humic acid may be examined in more detail. In all there were 48 comparable pairs of flasks with and without humic acid *A* and in 43 of these pairs there was more nitrate in the flask with humic acid. This fact alone is sufficient to demonstrate that humic acid caused some nitrate formation.

Table VII. *Recovery of* N *(in mg. per kg. soil) as* NH_3 *and* NO_3 *from humic acid* A. *Mean effect of humic acid in presence and absence of* 15 *mg.* N *as ammonium sulphate.*

	Time in weeks					
Soil	2	4	6	8	17	26
Rothamsted	1	4	4	5	10	10
Saxmundham	2	3	5	8	4	8
Tunstall	1	0	3	3	4	1
Woburn	0	4	2	4	−1	3
Mean difference between heavy (R. + S.) and light (T. + W.) soils	1·3	1·8	2·3	3·0	5·2	7·2

The results given in Table VII show that the extra nitrate due to humic acid is greater in the two heavy soils than in the two lighter ones, and further that the excess of nitrate production from humic acid in the heavy over that in the light soils increases most regularly with time. This differential effect of heavy and light soils on the rate of nitrate accumulation from humic acid accounts for the greater part of the interactions between treatment and soil and between treatment and time already mentioned. Its regular change with time forms but one of the 90 degrees of freedom in the highest order of interaction used for estimating the laboratory error, but separating it from the other 89 degrees would have only a trivial effect on this estimate of error. The increased nitrate from humic acid, especially in heavy soils, may be due not merely to a direct nitrification of its organic nitrogen but to improved physical conditions, such as better crumb structure, leading to a more complete oxidation of the soil organic matter. The fact that the effect is associated with heaviness rather than with soil reaction or reserves of nitrifiable material would point to this indirect effect but it is naturally impossible to decide the mechanism from these experiments alone.

POT-CULTURE EXPERIMENTS, 1932.

Pot cultures with barley followed by mustard were carried out in quadruplicate on the four soils and with the seven manurial treatments used in the flask experiments. Each pot contained 10 kg. of soil and ammonium sulphate was given at the rate of either 0·152 or 0·400 gm. of nitrogen per pot. The organic manures throughout supplied 0·400 gm. of nitrogen per pot (the ones with humic acid and ammonium sulphate had 0·4 gm. nitrogen and 0·152 nitrogen respectively in these forms and not a total of 0·400 gm. nitrogen as in the laboratory experiments). Each pot had a basal dressing of 2 gm. of dipotassium hydrogen phosphate. A pedrigree straw of Goldthorpe barley, graded to 0·05–0·06 gm. per seed, was sown on March 31st, 1932, at the rate of six seeds per pot and thinned out on April 4th to three plants per pot. The ears and straw of each pot were oven dried and weighed and the produce of replicate pots bulked for threshing and nitrogen determinations.

After the barley harvest the soil of each pot was thoroughly remixed and a further 2 gm. of potassium phosphate added. White mustard (*Brassica alba*) was sown on August 22nd, thinned on September 8th to three plants per pot, and harvested on October 28th. All mustard yields were low and generally large barley crops were followed by small mustard crops. The growth of the barley and the decomposition of its residues so completely exhausted the supply of available nitrogen that they masked any residual effect from the relatively slow decomposition of the organic manures. In fact the excess of nitrogen in the manured crops over that in the unmanured ones was less for the two crops, barley and mustard, than for the first alone.

The yields of dry matter in barley grain and barley straw are plotted in Fig. 2 against the mean nitrogen recoveries from the same treatments in the laboratory nitrification experiments (a slight correction was made in treatment 6 for the different amounts of humic acid used in the two series). For all soils there was a sufficient range of yields to reveal differences in the efficiencies of the fertilisers. The Rothamsted soil gave much higher yields than the others.

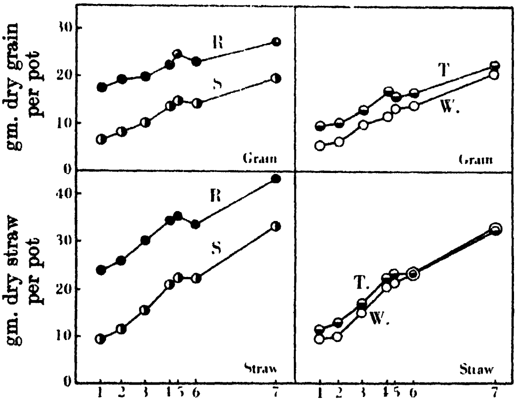

Fig. 2. Grain and straw yields in gm. dry matter per pot for seven fertiliser treatments in four soils, plotted against mean recovery of inorganic nitrogen in flask nitrification experiments (averaging four soils and all times of analysis) (Table VI).

The effects due to fertilisers were so closely similar in the four soils that it is unnecessary to tabulate the values for individual soils. The discrepancies between the relative effects in the four soils (*i.e.* the interaction between soils and treatments) may be used to provide a standard error with which to test the average response to treatment when the four soils are averaged. Table VIII gives the yields, nitrogen percentages, and total nitrogen contents of the crops averaging, first, the four soils and, second, the seven treatments. As in the nitrification experiments the effects of the ammonium humates are never significantly above those of ammonium sulphate equivalent to the ammonium of the ammonium humates. There is thus no definite evidence of any benefit from the humic

Table VIII. *Yields and nitrogen contents (in gm. per pot of* 10 *kg. soil) for barley grain (G), barley straw (S.) and mustard (M.) in pot cultures in four soils.*

	Nitrogen added		Yield of dry matter			Nitrogen % in dry matter			Total nitrogen in crops			
	NH_3	Total	*G.*	*S.*	*M.*	*G.*	*S.*	*M.*	*G.*	*S.*	*G.+S.*	*G.+S.+M.*
Results for 7 treatments, averaging 4 soils:												
(1) Untreated	—	—	9·7	13·6	3·67	1·40	0·305	2·40	0·138	0·042	0·180	0·267
(2) Humic acid *A*	—	0·400	10·8	15·1	3·69	1·38	0·314	2·38	0·151	0·048	0·199	0·287
(3) Ammonium humate *D*	0·083	0·400	13·1	19·5	2·29	1·22	0·291	2·46	0·165	0·058	0·223	0·303
(4) Ammonium sulphate	0·152	0·152	16·3	24·8	2·91	1·22	0·286	2·47	0·200	0·072	0·273	0·344
(5) Ammonium humate *B*	0·152	0·400	17·1	25·7	2·97	1·22	0·288	2·56	0·211	0·075	0·286	0·360
(6) Ammonium sulphate + humic acid *A*	0·152	0·552	16·9	25·8	3·11	1·24	0·298	2·48	0·211	0·077	0·288	0·365
(7) Ammonium sulphate	0·400	0·400	22·7	35·6	2·94	1·40	0·360	2·42	0·320	0·129	0·448	0·519
Standard error			0·48	0·51	0·139	0·025	0·0069	0·052	0·0048	0·0018	0·0057	0·0072
Results for 4 soils, averaging 7 treatments:												
Rothamsted soil	—	—	22·0	32·4	5·00	1·41	0·328	2·53	0·310	0·106	0·418	0·545
Saxmundham soil	—	—	12·3	19·5	3·83	1·25	0·273	2·18	0·167	0·054	0·207	0·290
Tunstall soil	—	—	15·0	20·5	2·38	1·31	0·301	2·44	0·191	0·063	0·258	0·316
Woburn soil	—	—	11·6	19·0	1·70	1·22	0·322	2·66	0·139	0·062	0·201	0·246
Standard error			0·36	0·38	0·105	0·019	0·0052	0·039	0·0036	0·0013	0·0043	0·0054

material either directly from its organic nitrogen or indirectly through any stimulation or improvement in the physical conditions of the soil. The increases due to humic acid are insignificant in yields of barley grain but just significant in the yields of straw and in the total nitrogen contents of the barley grain and straw and of the two crops. These small effects may be taken as suggesting that a little nitrogen became available relatively late in the growth of the barley. Apart from this small effect the general results for the nitrogen percentages of grain and straw show with increasing yields a progressive fall to a minimum and then a rise. This is evidence that the barley plants obtained most of their nitrogen at a sufficiently early stage of growth to allow of its efficient utilisation for carbohydrate synthesis. Both in yield and composition the barley plants showed that they received rapidly available nitrogen in amounts almost proportional to the ammonium nitrogen added in the fertilisers; only for humic acid was there any suggestion of a slight production of slowly available nitrogen. The general conclusions are thus identical with those from the laboratory nitrification experiments.

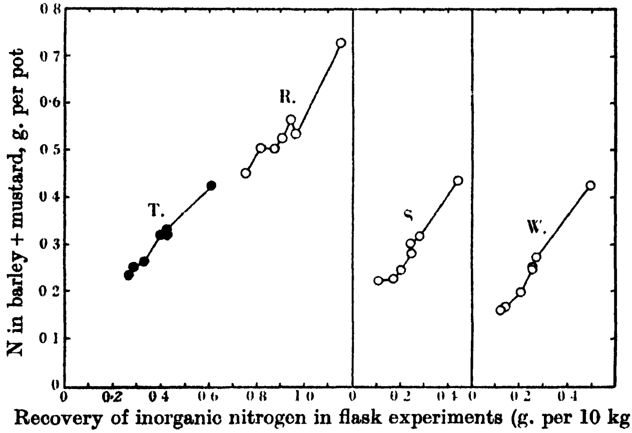

Fig. 3. Total nitrogen contents of barley, grain and straw, and mustard plotted against mean inorganic nitrogen content for the same soil and treatment calculated from laboratory nitrification experiments (averaging all times of analysis).

Fig. 3 gives a detailed comparison for the four soils separately of the inorganic nitrogen found in flask experiments and that contained in the two crops of the pot experiments (the discrepancy between the amounts of humic acid used in treatment 6 in the two series is neglected). The points are joined in the order in which the fertiliser treatments are arranged in Table VIII. It is obvious that the technique for assessing the relative availabilities of nitrogen in the fertilisers gave results closely parallel to the amounts absorbed by the crops in the pot cultures for comparisons in a single soil. This must be regarded as establishing the value of the laboratory technique and also as showing that for barley as grown in pot cultures the effects of the humic materials are entirely determined by the readily available nitrogen they supply. The fact that such results were obtained in four soils selected to secure the widest possible contrasts greatly increases the likelihood that the conclusions will be applicable to a wide range of soil conditions in the field. It must be concluded that the first year effects of such humic materials are to be assessed in terms of their ammonia contents with the possible qualification that humic acid *A* may act as a source of a little slowly available nitrogen.

FIELD EXPERIMENTS.

Field experiments were undertaken in 1932 to study the fertiliser value of ammonium humate *B* and humic acid *A* under as wide conditions of soils and crops as possible. The patterns of the experiments varied according to the local facilities and requirements. At Rothamsted and Woburn the experiments were on kale which was selected as a relatively slowly growing crop likely to utilise nitrogen over a long period. There were experiments on mangolds at Wye and Welshpool and on sugar beet at Wye and Tunstall. Four centres had potato experiments and three barley experiments on uniform plans.

Details of the previous cropping, layout and individual plot yields are given in the Rothamsted Report for 1932. Only summaries of the final yields and the relevant standard errors will be given here.

At Tunstall an experiment was made on sugar beet on a light sand to test ammonium humate supplying the same ammonia nitrogen as a standard dressing of ammonium sulphate (0·4 cwt. of nitrogen per acre). Over 1 ton of ammonium humate was required per acre. The test was made by splitting the 16 plots of a Latin Square experiment into humate and sulphate halves at random and was sufficiently sensitive to establish as significant a mean difference of only 2 per cent. in yield of roots, but the difference between the yields from the two manures fell below this amount.

The three barley experiments failed to reveal significant differences in grain yield between treatments when the experiments were considered individually, but the average of the three experiments showed that both sodium nitrate and ammonium sulphate increased the grain yields significantly and sodium nitrate gave a significantly higher yield than ammonium humate with equal total nitrogen. Ammonium humate gave about half the yield given by ammonium sulphate. The mean recovery in the grain of added nitrogen was 23 per cent. for ammonium sulphate and 9 per cent. for ammonium humate. The yields of barley straw showed wider differences than those of grain. At two of the centres—Wellingore and Sparsholt—there were significant yield differences of the type shown by the average grain yields for the three.

Table IX. *Experiments on barley*, 1932.

	O	B	S	N	
	No nitrogen	Ammonium humate	Ammonium sulphate	Sodium nitrate	Standard error
Grain yield, cwt. per acre:					
Wye, Kent	27·1	27·8	30·0	29·8	1·32
Sparsholt, Hants	22·4	24·7	25·4	27·0	1·33
Wellingore, Lincs	29·0	29·9	30·9	30·7	0·96
Straw yield, cwt. per acre:					
Wye	32·0	33·2	38·5	38·8	2·10
Sparsholt	22·0	24·8	28·9	29·5	1·38
Wellingore	29·1	30·7	33·5	36·4	1·20
Nitrogen % of dry matter in grain:					
Wye	1·24	1·24	1·28	1·30	—
Sparsholt	1·31	1·32	1·38	1·37	—
Wellingore	1·50	1·53	1·60	1·70	—
Percentage recovery in gm. of added nitrogen:					
Wye	—	3	20	21	—
Sparsholt	—	13	23	31	—
Wellingore	—	10	26	36	—

Significant differences in straw yield: at Wye, $S=N>O$; at Sparsholt, $S=N>B=O$; at Wellingore, $S=N>O$; $\frac{1}{2}(S+N)>B$.

The potato experiments were on small plots and none of the differences attained the rather high levels required for significance.

The Wye sugar-beet experiment gave significant differences for the three levels of nitrogen as ammonium sulphate (0, 0·15 and 0·4 cwt. per acre) but failed to distinguish between ammonium humate and ammonium sulphate of equal ammonium content. The Wye experiment on mangolds proved to be the most sensitive of the series. Ammonium humate again failed to give higher yields than ammonium sulphate of equal ammonium content, in spite of the circumstance that the higher dressing of ammonium sulphate gave a further large increase in yield, but humic acid gave a significant increase over no nitrogen. At Welshpool however the addition of humic acid with ammonium sulphate reduced the yield of mangold tops below that from ammonium sulphate alone.

The kale experiments provide conditions somewhat approaching

Table X. *Experiments on root crops, 1932. All yield in tons per acre.*

Treatment		*O* None	*A* Humic acid	*S*1 Ammonium sulphate	*S*1 + *A* Ammonium sulphate + humic acid	*B* Ammonium humate	*S*2 Ammonium sulphate	*N* Sodium nitrate	Standard error	Significant differences
N added as NH_4 or NO_3, cwt. per acre		—	—	0·15	0·15	0·15	0·4	0·4	—	—
Organic N added, cwt. per acre		—	0·40	—	0·25	0·25	—	—	—	—
Total N added, cwt. per acre		—	0·40	0·15	0·40	0·40	0·4	0·4	—	—
Centre	Crop									
Wye, Kent	Mangolds	13·7	15·6	17·3	—	18·6	20·9	—	0·48	*S*2 > *B* = *S*1 > *A* > *O*
Welshpool, Mont.	Mangolds, roots	—	—	12·9	12·2	13·5	15·6	—	0·58	*S*2 > others
” ”	Mangolds, tops	—	—	5·6	4·5	5·2	6·2	—	0·19	*S*2 > *S*1 = *B* > *S*1 + *A*
Wye, Kent	Sugar beet, washed roots	12·0	—	12·7	—	12·8	13·8	14·0	0·18	*N* = *S*2 > *B* = *S*1 > *O*
”	Sugar beet, tops	7·6	—	8·3	—	8·4	9·6	10·4	0·34	*N* = *S*2 > *B* = *S*1 = *O*
Burford, Oxford	Potatoes	—	—	7·6	8·5	7·7	8·5	—	0·59	—
Tonbridge, Kent	Potatoes	—	—	10·0	10·0	10·2	9·8	—	0·38	—
Godalming, Surrey	Potatoes	—	—	10·1	9·1	10·6	10·2	—	0·32	—
Hull, Yorks	Potatoes	—	—	11·1	10·8	10·9	11·2	—	0·46	—

those of the market-garden crops for which slowly acting organic manures are highly favoured. The differences in yield and nitrogen contents were small. At Rothamsted but not at Woburn the heavier dressing of ammonium sulphate gave a significantly higher yield than the lower one showing that the crop was capable of responding to added nitrogen. There were, however, no responses to the organic forms of nitrogen. At Woburn humic acid gave a slightly lower yield and nitrogen content than the unmanured plots.

Table XI. *Kale experiments at Rothamsted (R.) and Woburn (W.)*, 1932.

	O	*A*	*S*1	*B*	*S*2	
	No N	Humic acid	Ammonium sulphate	Ammonium humate	Ammonium sulphate	Standard error
N added as NH_4, cwt. per acre	0	0	0·145	0·145	0·4	—
N added as organic matter, cwt. per acre	0	0·4	0	0·255	0	—
Fresh crop, tons per acre:						
R.	12·6	12·9	13·8	13·8	15·4	0·38
W.	17·6	16·9	18·8	18·0	18·8	0·62
Dry matter, tons per acre:						
R.	1·87	1·94	2·11	2·09	2·17	—
W.	2·96	2·82	3·12	2·97	3·08	—
N in crop, cwt. per acre:						
R.	0·65	0·69	0·69	0·72	0·79	—
W.	1·17	1·09	1·19	1·24	1·24	—
Percentage N recovery:						
R.	—	10	18	26	34	—
W.	—	(−20)	16	18	18	—

Significant results in fresh crop: at Rothamsted, $S2 > S1 = B > O$; at Woburn, none.

When the whole of the comparable results in the above series of experiments was averaged it was found that the slight superiority of ammonium humate over ammonium sulphate of equal ammonium content was too small to be regarded as more than fortuitous. The single significant positive result from humic acid must be regarded as offset by a negative result. The results for a wide range of soil and crops show that the fertilising value of these humic materials in a single season may be assessed from their ammonium contents as determined in the Regulations of the Fertiliser and Feeding Stuffs Act.

SUMMARY.

1. Humic acids and ammonium humates prepared by a patented process of gentle oxidation of coal were examined as fertilisers by laboratory nitrification experiments and pot-culture tests on four soils

and by a number of field experiments on a range of soils and crops during a single season.

2. In all tests the effects of ammonium humate could not be distinguished from those of ammonium sulphate of equal ammonium content. The nitrification tests and the pot cultures afforded some evidence of a slow production of nitrate or available nitrogen from the humic acid.

3. In the field experiments as in the pots there was no clear evidence of any fertiliser value apart from that due to the ammonium present.

4. The close agreement between laboratory measurements on nitrate accumulation and yields and nitrogen contents of barley for seven treatments in four soils shows that the laboratory technique afforded an adequate measure of the availability of the fertiliser nitrogen.

ACKNOWLEDGMENTS.

We wish to record our indebtedness to Mr F. McNaughtan of the Government Agricultural Chemistry Laboratory, Kenya, who carried out most of the 1932 laboratory work during a period of study leave, and to a number of local workers, whose names and addresses are given in the Rothamsted Report for 1932, for conducting the necessary field experiments under Rothamsted supervision.

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THE VALUE OF A UNIFORMITY TRIAL IN FIELD EXPERIMENTATION WITH RUBBER.

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FIELD experiments are subject to two main potential sources of error: (1) variation due to outside influences such as differences in soil fertility, exposure to wind, disease, etc., and (2) the inherent variability of the material used. By the methods of plot arrangement evolved by Fisher these sources of error can be estimated with precision and given due weight in the analysis of the results. In an experiment where the heterogeneity of the soil or plant material is considerable, however, the residual error is high and the accuracy of the experiment correspondingly low. On the assumption that the disparity between the yields of the different plots is relatively constant, one would suppose that the value of such an experiment might be legitimately enhanced by utilising previous crop records. In the past the "percentage increase" method has sometimes been used for correcting the experimental yields, but this method is statistically unsatisfactory and may actually lead to a loss rather than a gain in precision.

The inference that the yield of a plot in one year is any guide to its yield in another implies that the expectation of yield is well represented in terms of the previous performance by a linear regression function. If the yields in the preliminary and experimental periods be denoted by x and y respectively, then the appropriate regression coefficient b is given by the ratio $\frac{\text{Cov}_{xy}}{V_x}$, where Cov_{xy} is the covariance of the preliminary and experimental yields, or the mean product of their deviations from their means, and V_x is the residual variance of the preliminary yields. The yields in the experimental period are to be adjusted by means of this coefficient, so that comparisons of adjusted yields become, in fact, comparisons of the quantities $(y-bx)$.

Now $$(y-bx)^2=b^2x^2-2bxy+y^2,$$

so that, in obtaining the analysis of variance of the adjusted yields, the sum of squares in any line can be calculated by multiplying x^2 by b^2, xy by $-2b$, and y^2 by unity, and adding the products.

Sanders (1) showed that the error variance of the adjusted yields ($V_{y.x}$) can be conveniently calculated from the formula

$$V_{y.x} = V_y - \frac{(\text{Cov}_{xy})^2}{V_x},$$

the resultant figure being corrected for the one degree of freedom used in employing the regression. The increased precision gained by using the previous records as a uniformity trial is then given by the ratio $V_y : V_{y.x}$.

Sanders used this method for investigating a uniformity trial on annual crops in which each year's data referred to a different crop. In one field the relative plot yields showed no constancy, and the previous figures were therefore of no value. In another field, however, the differences between the plot yields did show a tendency to persist, and by using a regression on the mean yield of three previous years the precision of the experiment was increased by nearly 150 per cent. In view of the loss in time and increase in labour and expenditure incurred in compiling records in a previous year or years, it is doubtful, however, on the basis of these results, whether the method would usually justify itself for annual crops.

With a perennial crop from which the yields in successive years are derived from the same individual plants, a higher correlation is to be expected. Eden (2), working with tea, has demonstrated a striking reduction in error by utilising the results of preliminary pluckings. The precision of the experiment was increased more than sixfold, that is to say that without the previous records the replications would need to have been more than six times as numerous to achieve the same degree of accuracy.

Field experimentation with mature rubber (*Hevea brasiliensis*) has at present to be conducted on a seedling population of great variability; the annual yield of individual plants in any one field may, in extreme cases, vary from less than 1 lb. up to 100 lb. of rubber. The trees are planted at a density of approximately 100 per acre, and in order to keep soil heterogeneity within reasonable bounds it is desirable that the number of individual plants in a plot be relatively small. Lord (3) computed that the optimum plot size was approximately twenty-four trees. With such small plots the crop from an exceptional individual tree assumes important proportions, and the yields of the several plots are liable to show considerable diversity. The yield of an individual tree remains fairly constant from year to year, and a substantial benefit as the result of a previous uniformity trial may therefore be anticipated.

THE DATA.

While enjoying the hospitality of Rothamsted Experimental Station the writer had the opportunity to examine ten years' yield records of about 1000 individual rubber trees planted in Sumatra. These figures were given to the Statistical Department by Mr J. Grantham of the United States Rubber Plantations Incorporated, to whom the writer is indebted for permission to publish the results of the work. At the suggestion of Prof. R. A. Fisher, then Chief Statistician at Rothamsted, these figures were analysed with a view to determining the utility of previous crop records in field experimentation with rubber.

As stated above, the data consist of individual tree records of nearly 1000 ordinary seedling rubber trees, planted in 1911 and thinned out in 1918 and subsequently. From the chart accompanying the records a 5 × 5 Latin square of twenty-five tree plots was marked out, barrier rows being allotted as if a real test of five manurial treatments (replicated five-fold) were involved. The plot yields for any year were calculated from the yields of the individual trees in the several plots.

In order that the trial should be representative of results likely to be obtained with fully mature rubber, the last four years' records, *i.e.* 1926–9 were selected, the age of the trees being then 15–18 years. The method of enquiry was to regard 1926 as the preliminary year, and to determine how far the residual variance was reduced by utilising these yields with 1927, 1928 and 1929 respectively as supposedly experimental years.

Table I. *Yields for "Preliminary" year* 1926.

851	825	837	975	1015	4503
840	945	776	1108	970	4639
925	920	968	1009	1026	4848
869	1028	735	730	892	4254
979	931	1012	1070	989	4981
4464	4649	4328	4892	4892	23225

General mean = 929·0

Table II. *Yields for "Experimental" Year* 1927.

906	858	836	923	1023	4546
957	997	846	1126	995	4921
978	1042	1003	1061	1049	5133
956	1054	764	837	946	4557
1110	956	1095	1180	995	5336
4907	4907	4544	5127	5008	24493

General mean = 979·7

The method is worked out in detail for the "experimental" year 1927. Tables I and II give the plot yields for the years 1926 and 1927 respectively, the yield figures given by Grantham being divided by 100 and expressed to the nearest whole number.

The analyses of variance for the two years are given in Tables III and IV.

Table III. *Analysis of variance "Preliminary" year* 1926.

Variance due to	Degrees of freedom	Sum of squares	Variance	S.D.
Rows	4	65,437	16359	
Columns	4	51,057	12764	
Error	16	125,998	7874·9	88·74
Total	24	242,492	10104	

Table IV. *Analysis of variance "Experimental" year* 1927.

Variance due to	Degrees of freedom	Sum of squares	Variance	S.D.
Rows	4	90,698	22674·5	
Columns	4	31,145	7786	
Error	16	118,744	7421·5	86·15
Total	24	240,587	10024	

Since there were no actual treatments, 16 degrees of freedom are used for the estimation of error. Despite the large variance eliminated by rows, the residual variance in 1927 is 7421·5, giving a standard error of a single plot of about 8·79 per cent., and for the total of five plots of about 3·93 per cent.

The analysis of covariance between 1927 and 1926 is obtained by using the sums of products for the two years instead of the sums of squares for either one year, and is as follows:

Table V. *Analysis of covariance* 1927 × 1926.

Variance due to	Degrees of freedom	Sum of products	Covariance
Rows	4	75,610	
Columns	4	38,872	
Error	16	105,874	6617·1
Total	24	220,356	

Substituting the figures for 1927 (y) and 1926 (x) in the formula given above, we obtain

$$V_{y.x} = V_y - \frac{(\text{Cov}_{xy})^2}{V_x} = 7421{\cdot}5 - \frac{(6617{\cdot}1)^2}{7874{\cdot}9} = 1861{\cdot}4.$$

But in employing a linear regression one degree of freedom is used up, and we have finally

$$V_{y.x} = \frac{1861{\cdot}4 \times 16}{15} = 1985{\cdot}5.$$

The residual variance has thus been reduced from 7421·5 to 1985·5, and the increased precision of the experiment is measured by the fraction

$$\frac{V_y}{V_{y.x}} = \frac{7421{\cdot}5}{1985{\cdot}5} = 3{\cdot}74.$$

In other words, if the year 1927 were to stand alone, the number of replications necessary to achieve the same degree of accuracy would be 5 × 3·74, or approximately 19.

The same procedure has been followed with the years 1928 and 1929, the regression in all cases being on the preliminary year 1926.

The following table gives the increased precision $V_y : V_{y.x}$ for the several years:

	$V_y : V_{y.x}$
1927 × 1926	3·74
1928 × 1926	2·52
1929 × 1926	2·15

These figures show that a considerable gain in precision is effected by the application of this method, the biggest advantage being obtained when the experimental and preliminary years are consecutive. It is probable that a somewhat greater reduction in error would be achieved by employing a regression on the mean of a number of previous years, but in experimenting with rubber such figures are most unlikely to be available and it would probably be impracticable to delay the experiment for several years in order to obtain them.

The variance of the 1927 yields adjusted for 1926 is analysed in Table VI, using the equation

$$S\,(y - bx)^2 = S\,(y^2) - 2bS\,(xy) + b^2S\,(x^2).$$

Here b is the regression coefficient on the residuals after allowing for row and column effects, and is equal to

$$\frac{6617{\cdot}1}{7874{\cdot}9} = 0{\cdot}840.$$

Table VI. *Analysis of variance of adjusted yield* 1927/1926.

Variance due to	Degrees of freedom	Sum of squares	Variance	S.D.
Rows	**4**	**9,845**	**2461·2**	
Columns	**4**	**1,866**	**466·5**	
Error	**15**	**29,782**	**1985·5**	**44·56**
Total	**23**	**41,493**	**1804·0**	

The standard error of a single plot is now reduced from 8·79 per cent. to about 4·55 per cent., and of the total of five plots from 3·93 per cent. to about 2·03 per cent.

As an example of method the row totals for 1927 have been adjusted by subtracting from any experimental yield y the factor $b\,(x-\bar{x})$, where $\bar{x}$ is the mean row total for 1926. The adjusted and actual figures are given in Table VII.

Table VII. *Row totals* 1927.

Actual totals	Adjusted totals
4546	4665
4921	4926
5133	4962
4557	4885
5336	5054

It is clear, at a glance, that the variation in the adjusted row totals is considerably less than in the actual totals, and a study of the analyses of variance of the original and corrected yields (Tables IV and VI) shows that whereas the original differences were significant by the z test, the adjusted differences are not so. This implies that whatever fertility or other differences were eliminated by rows are more or less constant over the two years, and are therefore equally well eliminated by the regression. This is the reverse of the results obtained by Eden (2) with tea. Discussing the tea figures, Fisher (4) points out that the elimination of positional variance by means of rows and columns is actually more important in the adjusted than in the unadjusted yields. With the figures presented in this paper, on the other hand, the error has actually been increased (though only by chance) by the removal of row and column effect.

A practical point to be noted is that the regression is a more effective means of reducing error than the removal of positional variance; the elimination of rows and columns has only reduced the variance from 10,024 to 7421 (Table IV), whereas the regression based on the total sums of squares (*i.e.* ignoring rows and columns) reduces it to 1754. This suggests that results of some value can be obtained with rubber where previous records are known, but where the arrangement of the plots does not permit elimination of the positional effect.

PRACTICAL CONCLUSIONS.

The results of this very brief and incomplete investigation show that the utilisation of previous crop records can be of considerable value in field experimentation with rubber. From a practical standpoint, also, the method should be well suited to this crop. A trial of fertiliser treatments, for example, is a long-range investigation in which the results cannot be fully evaluated for some years, and the loss of time and increase in labour incurred in compiling one year's preliminary records are of small importance if the value of the subsequent experiment is to be materially enhanced. The figures show, however, that the advantage of the correction becomes gradually less marked as the gap between the "experimental" and "preliminary" years widens, and it is probable that the main value of the uniformity trial is in enabling the experimenter to draw sound preliminary conclusions, and to avoid false deductions, in the early years. This would more than counterbalance the loss of one year involved.

A consideration of practical details would be out of place in this paper. One point, however, must be mentioned. There is often a substantial difference in yield from the two sides of an individual tree, and it would seem to be important, therefore, that the uniformity trial should include equal tapping periods on the two panels. This is an easy matter under Ceylon conditions where an annual or six-monthly change of the panel is the usual practice, and it may be concluded that one year's records, with a "change-over" after six months, should prove a valuable precursor to any major field experiment with rubber in Ceylon.

SUMMARY.

1. Sanders' method of utilising previous crop records to correct experimental results by means of a linear regression is briefly described.

2. The method is applied to yield figures from rubber trees in Sumatra, and the precision of a dummy experiment is thereby increased nearly fourfold when the "preliminary" and "experimental" years are consecutive. When the "experimental" year is three years later than the "preliminary" year, the error variance of the adjusted yields is reduced to about a half.

3. It is concluded that not only has the method of correction been of value in the particular instance investigated, but that a uniformity trial utilised in this way should be of practical value in any major field experiments with rubber.

The writer is greatly indebted to Prof. R. A. Fisher, F.R.S. and Mr F. Yates of the Statistical Department, Rothamsted Experimental Station, who suggested this line of investigation and guided its progress throughout, and to Mr T. Eden, of the Tea Research Institute of Ceylon, who kindly read and criticised this paper.

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THE DURABILITY OF MOLE DRAINS.

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(With Plates I and II.)

MOLE draining or its equivalent has been practised on clay land for many years; indeed, according to Richardson and Fussell, writing in the *Journal of the Ministry of Agriculture*, 1922, a patent for a mole plough was taken out in England in 1797. Fowler's mole plough appeared about 1850, and since then this type of implement, drawn by steam engines, has played an important and valuable part in the farming of the heavy arable areas of the eastern counties. Dr R. McG. Carslaw and Mr A. W. Menzies-Kitchin have recently (1933) collected much useful information on mole draining practice in East Anglia. The data were obtained from some 80 farms, and are summarised in *Report No.* 21 of the Farm Economics Branch of the Cambridge University Department of Agriculture. Dealing with the mechanical side of the subject, the *Report* states "...it was rather surprising to find that tractors had been used for draining only on 3 out of 75 farms, and that on two of these, steam engines had also been employed. On one farm...a team of 10 horses, and on two others, oil engines....On the remaining farms, representing 95 % of the total, power was supplied by steam engines." In respect of the durability of mole drains the *Report* states "The data showed considerable variation in the length of life of mole drains, but the average life appeared to lie round about 13 years, with an average range of from 8 to 19 years.... Silting, stated generally to be caused by the presence of loose sand and/or gravel in the clay subsoil, was the most common cause of failure."

If data such as are summarised in this *Report* could be correlated with information on the physical properties of the soils of the 80 farms concerned, no doubt valuable information would be forthcoming as to some of the factors which influence the durability of mole drains. By the courtesy of Dr Carslaw, the writer has been enabled to study the returns more closely. The farms can be grouped into seven main areas, as follows:

				Mean effective life of mole drains	
Nature of soil	Parish	County	No. of farms examined	Arable land (years)	Grass land (years)
1. Boulder Clay on Chalk	Alpheton Brent Eleigh Monks Eleigh	West Suffolk	9	16·7	18·6
2. ,,	Clare Haverhill Helion Bumpstead Steeple Bumpstead	West Suffolk and Essex boundary	22	12·6	12·7
3. ,,	Wimbish	Essex	9	10·7	13·0
4. Boulder Clay on London Clay	Thaxted	,,	12	14·8	15·2
5. London Clay	Horndon Laindon	,,	5	10	—
6. Boulder Clay on Chalk	—	West Cambs	5	10·5	—
7. Boulder Clay on Oxford Clay	—	Hunts	4	8·5	—

There is considerable variation in the means of all seven groups. The numbers of cases concerned are small in three of the areas and render them useless for purposes of comparison. The same general criticism applies to the figures pertaining to grass land as a whole—only half of the informants expressed an opinion. Between the longevity of mole drains on grass land and on arable land on the same type of soil there seems to be very little difference, but in the farmers' opinion, what there is favours the former. A comparison of the figures for the four larger groups does bring out more marked differences. Both on the Boulder Clay over Chalk in the Brent Eleigh district of Suffolk and on the Boulder Clay over London Clay in the Thaxted area of Essex, a longer useful life is attributed to mole drains than is the case on the Boulder Clay over Chalk in the Haverhill area of the Suffolk-Essex boundary and the Wimbish area of Essex. Statistical analysis reveals significant differences between districts 1 and 2, and between 3 and 4. It is interesting to note that the older forms of mole draining commonly practised in this part of England before the advent of steam tackle had a similar useful life. The Rev. Copinger Hill, describing them in the *Journal of the Royal Agricultural Society* in 1843, gives a figure of 12–20 years. It should be remembered that in all these cases, both in the older hand work and in the cases reviewed in the report, the depth of the moles was from 20 to 30 in.

Dr Carslaw's information on the causes of deterioration of mole drain systems may be summarised as follows:

Nature of subsoil	41	instances
Passage of heavy machines etc.	8	,,
Operations of burrowing animals	16	,,

The first group was characterised in various ways; in 16 cases the trouble was described as uneven subsoil, in 10 cases as the presence of sand in the subsoil, in 8 cases as the presence of gravel in the subsoil, and in 7 cases as the accumulation of silt in the channels. The physical constitution of the subsoil is evidently the most potent factor and the presence of even a few sandy or gravelly patches in the clay may be a cause of weakness in the whole system.

The figures above represent the considered opinions of practical exponents of mole draining, based on long individual observation and experience. It is a matter of great difficulty to investigate the points at issue directly. It is obviously impossible to watch the deterioration of a working mole channel over a period of years by direct vision. One can isolate a length of mole and look through it, but a view of 6–12 ft. length of wall in perspective through a 2 in. aperture, is not very illuminating. The isolation of such a length generally means putting it out of action, and the actual digging operation necessary to expose it, inevitably causes some deformation of the exposed ends. It is possible, however, to take plaster casts of the interior of mole channels and so obtain the advantages of direct vision in examining the surface of the walls from time to time and in varied circumstances. The procedure adopted in the investigations here described was to dig a trench at right angles to the direction of the moles until two or three were exposed. A hole was then dug on the line of the mole 2–3 ft. away, so as to isolate this length. Clay cups were then fashioned about the two open ends and plaster of Paris was poured into the cup at the lower end until the channel was filled. It was left an hour or more to solidify, the block of soil between the two holes was dug out intact and the plaster cast was finally dissected out at leisure. The accompanying photographs show some typical casts obtained on the University Farm at Cambridge, while the life-history of mole drains was being studied from the time they were drawn. The mole channels observed were all drawn in fields of the same general type of soil on Gault Clay. The subsoil is as a rule a fairly uniform yellow grey clay, though isolated patches of gravelly clay are encountered. The clay content of the subsoil from 10 to 25 in. depth is fairly uniformly 50 per cent.

The disturbance of the ground which mole draining entails is well known. Pl. I, fig. 1 shows the nature of the fissures immediately after the passage of the mole plough. These moles were drawn 20–24 in. deep. The cast is lying on its side and the fissures as represented by the plaster ridges are vertical in the soil but inclined to the main slit which they join at an acute angle in the direction opposite to that of the travel of the mole plough. The lower half of the sides and the bottom of the mole channel are often fissured in the same direction. If it be the fact that in heavy clay soils drainage takes place only in the surface inches or cultivated layer and thence via the slit to the mole channel, then the nature of these fissures is of some importance and their direction gives point to the prevailing practice with steam tackle of pulling the mole plough uphill only. (This was the method adopted in 66 out of 74 instances in Dr Carslaw's survey.) Fractures once made persist for a long time, as witness the annual gaping of mole slits during summer drought. During the exceptional drought of 1933, the whole lay-out of a piece of mole draining which was done in 1917 on the Cambridge University Farm became apparent in this manner.

Pl. I, fig. 2 is an example of a very smooth channel freshly drawn by a tractor operating with a winch in an even clay subsoil; very little fissuring from the mole channel was found. Pl. I, fig. 3 shows the effect of the presence of flints and pebbles in a small patch of the same clay subsoil, only a few yards away, on the same occasion. The vertical black patches indicate the ends of the cast proper and small light patches in between mark the smooth portions of the wall. A short length of the straight bottom edge of the channel can be seen towards the left. The rough incrustations of plaster show the deeply honeycombed and broken wall of the channel. It is not surprising that a section of channel of this nature may break down quickly, to the detriment of the whole length of the mole above it. Pl. I, fig. 4 is a side view of a cast taken from the same system as fig. 1, 20 months after its origin and in a damp condition. It clearly shows the nature of the falls from the roof and sides of the channel, the lumps lying where they fell. Much of the smooth original surface is still intact (in this case estimated at about 35–50 per cent.). In the moles as drawn, the vertical section was regular and ovoid in shape, 3·7 in. deep and 2·5 in. broad. After 20 months the cross-section was irregular, roughly ovoid in the upper half, but indiscernible in the lower half owing to the fallen lumps of clay. The depth of the channel in this cast varies from 2·3 to 3·5 in., while the breadth varies from 1·5 to 2·6 in. The white ends of the broken casts in Pl. I, fig. 5 show

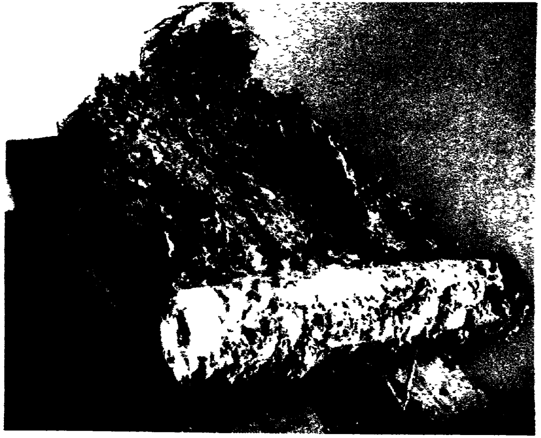

Fig. 1. Showing lateral fissures from mole slit and oblique fissures from bottom of mole channel.

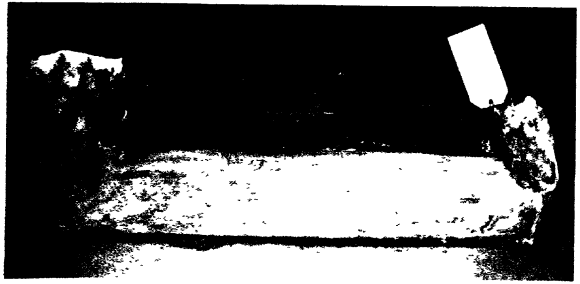

Fig. 2. Perfectly smooth mole channel.

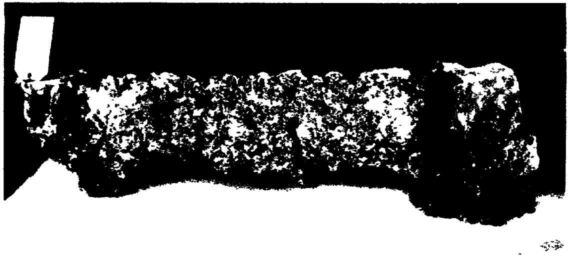

Fig. 3. Mole channel as affected by presence of gravel in clay subsoil.

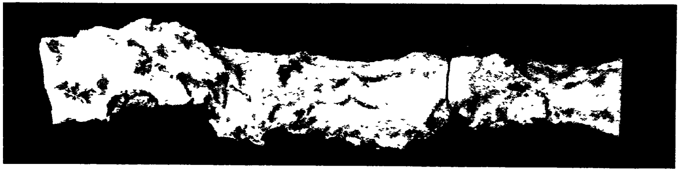

Fig. 4. Mole channel 20 months after being drawn.

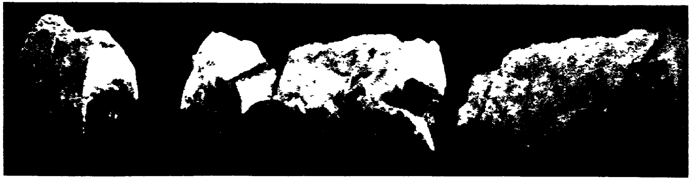

Fig. 5. Showing shape of cross-section of mole channel 20 months old.

the varying shape of the cross-section. These moles were still functioning well and it would appear that though falls had taken place everywhere to a considerable extent, the pieces of clay were lying intact where they had fallen and had not collapsed into "silt." The channels, though irregular and obstructed, must have been still open throughout their length. In this connection it may be stated that it is only on rare occasions that the drainage water from these systems is at all turbid.

Pl. II, fig. 1 is a photograph of a cast taken from the same system in the height of the 1933 drought, 32 months after the moles were drawn. At the time, the ground was a freshly cleared stubble. The lines of the moles could be picked out by the surface cracks, though with difficulty, owing to the tilth and general small cracks which tend to obscure those due to the mole slits. But on digging, as soon as the cultivated soil was passed, it was found that the mole slit was wide open down to the channel and considerably beyond it—it was possible to dip a rod to a depth of 3 ft. 5 in. on the average without encountering solid earth. The actual channel was easily discernible but of course had no floor. In this photograph the upper and lower limits of the original channel have been partly marked in ink. Typical measurements of the cross-section are given below to supplement it.

Depth below surface (in.)	Width of slit (in.)	
0	Just visible	
6	¼	
9	½	
17	1	
21	1½	the mole channel
22½	2½	
24	1	
30	¾	
40	¼	

Within the length of the cast shown (2 ft. 3 in.) there were two considerable side cracks, roughly vertical and at right angles to the main slit (marked × in the photograph). In the actual channel there were many loose pieces of clay. A state of affairs such as this will probably result in the channel being much less regular when the autumn rains cause the clay to swell once more and must be the cause of marked deterioration of the whole system.

The normal expectation after a dry summer such as that of 1933 is that drains in general will be much later in commencing to run, after the incidence of winter rains. This effect has been considerably enhanced in the eastern counties by the fact that even up to January 13, 1934, no very great amount of rain had fallen. The cracks in heavy land were still open and although the soil in the neighbourhood of the mole channels was distinctly moist, no flow had taken place. Further casts taken at this date are depicted in side view and in cross-section in Pl. II, figs. 2 and 3. Some 9 ft. of channel in two different moles were cast and it was found that the channel was quite closed by falls at two points in one and at one point in the other. The part which was intact showed a considerable portion of its original surface but its dimensions were very much reduced:

Height of channel: maximum 4 in., minimum 1¼ in., mostly 2½ in.
Width of channel: maximum 1¾ in., minimum ¾ in., mostly 1¼ in.

The condition of similar mole channels after 7 years of useful life is shown in Pl. II, fig. 4. No vestige of the original surface remains, but the line of the slit is still visible as a slight ridge along the top of the cast. The bottom of the channel is very uneven owing to the fragments of clay lying in it. These, however, are no longer angular in shape or well defined; years of attrition by the flow of water and further weathering have rounded off their shape or reduced them to loose masses of smaller pieces. The cross-section of the channel is no longer elongated vertically but rather flattened horizontally:

Height of channel: maximum 3½ in., minimum 2 in.
Width of channel: maximum 4¼ in., minimum 2¾ in.

The taking of casts of mole drains has proved a useful method of following and recording the changes and decay to which they are subject. It would appear that fissuring, the very factor which is most potent in ameliorating the drainage of heavy clays, is the chief cause of the decay of the mole channels. Whether these fissures are produced naturally by the drying out and the contraction of the clay, or artificially by the disruptive effects of deep tillages or of mole draining, the effects are similar. After a dry summer, a heavy soil is usually dryer and more open during the following winter. The drains begin to run much later in the season and it is generally held that they function better. In any case the capacity of heavy soil to absorb water will in such circumstances enable it to deal with winter rains for a longer time by absorption alone, and subsequently the initially more extensive fissuring will confer on the soil a greater, if temporary, permeability. If, however, the drying out proceeds to the depth of the mole channels or beyond, as has been the case this last summer to a marked degree, the channels will probably suffer greater deterioration. More fragments flake off from their walls or fall down from the slits above, so that the chances of stoppage or

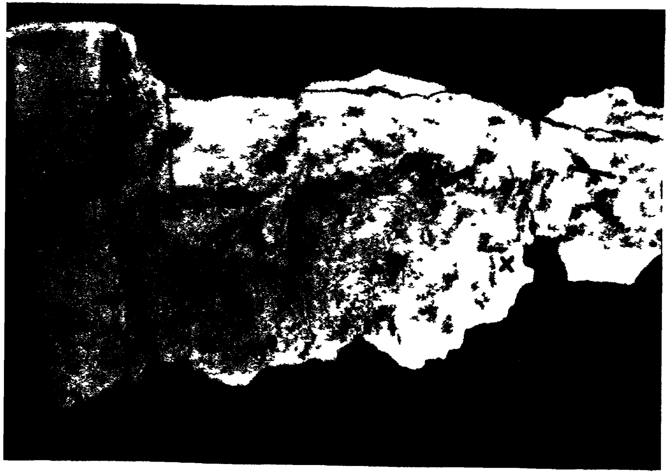

Fig 1 Condition of mole channel and slit during drought Limits of original channel marked by arrows prominent vertical transverse fissures

Fig 2 Mole channel closed again after autumn rains

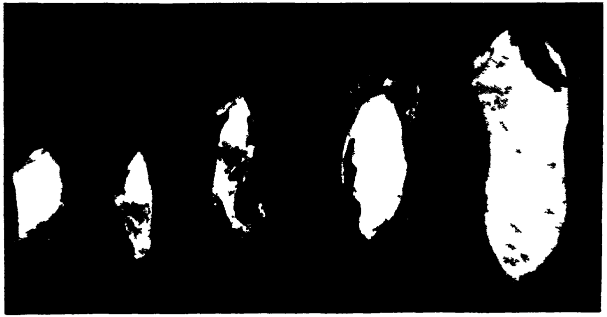

Fig 3 Mole channel in cross-section at various points in a length of 9 ft after 30 months of life

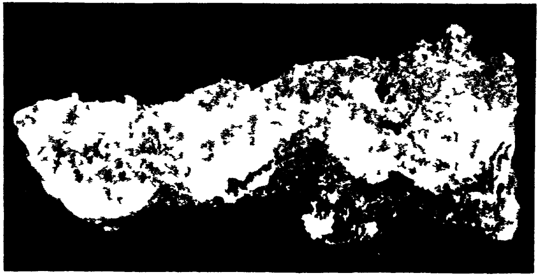

Fig 4 A mole channel after 7 years of life

"silting up" are greater. Turning to the effects of mole draining operations, it would appear that the upheaval and tearing effect which is apparent as the mole plough proceeds is all to the good, to the extent to which it occurs between the soil surface and the mole channel. A comparatively permeable strip of soil is produced to about 18 or 24 in. on either side of the mole slit, and this must make it easier for excess water at the surface to find its way into the mole channels. Fissuring in the walls of the channel itself, however, cannot be so favourably regarded, as it must be a cause of weakness and of earlier collapse of the walls. It would appear that such fissuring may be due to various causes. The presence of small stones or gravel in the clay subsoil is undoubtedly one, while another is the angle which the cartridge makes with the surface of the soil—the greater this is, the more numerous and substantial are the fissures in the wall of the channel. In the actual operation of mole drainage the fissuring of the walls might be overcome in various ways (1) by attention to the setting of the cartridge, (2) by the attachment of a bob to the cartridge, (3) by the use of a cylindrical bob, rifled and free to revolve on its axis.

The writer wishes gratefully to acknowledge the facilities afforded him by Prof. F. L. Engledow and Mr W. S. Mansfield on the Cambridge University Farm, and the helpful and critical interest which they have displayed throughout the investigations.

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THE EPIDEMIOLOGY OF PARASITIC GASTRITIS IN SHEEP.

OBSERVATIONS ON THE RELATIVE IMPORTANCE OF THE VARIOUS FACTORS CONCERNED IN THE DEVELOPMENT OF THE DISEASE.

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The most obvious lines of investigation for the discovery of some method of controlling parasitic gastritis in lambs are those which endeavour to find a means either of killing the parasitic worms in the stomach and intestine, or of destroying the free-living larval stages which are present in the soil. Both of these lines have been diligently followed by research workers in different countries throughout the world, numerous drugs have been tried for the cure of affected sheep and many substances tried for ridding the land of infective larvae; but apart from treatment with copper sulphate or carbon tetrachloride, to which only *Haemonchus contortus* responds, none has given promise of success.

Although the possibilities of these lines are by no means exhausted (particularly the possibilities of successful drug treatment), the solution to the problem is not forthcoming at the present time, and it is expedient to explore every other avenue most carefully to find out whether there is not some way in which the development of the disease may otherwise be checked.

The problems connected with the prevention of this disease are peculiar in that they refer, largely, to a hindrance of the multiplication of the parasites, these being so widely distributed that their presence in some, or all, of the members of any flock of sheep may be taken for granted, and so long as their number remains small no harm will result. At times, however, a mass increase takes place in the number of parasites, resulting in marked unthriftiness, and in some instances, in severe disease which may wipe out the greater part of a flock of lambs. As the worms do not multiply in the sheep, but require to be picked up individually from the pasture, anything which will help the lambs to resist the development of larvae taken up with the herbage, or will hinder their development on the soil, may be of value in keeping the numbers of parasitic worms within the limits of safety.

The study of the bionomics of the free-living larvae on the soil has taught us a good deal about their requirements as to moisture and temperature, the length of time taken in the hatching of the egg, the development of the first-stage and second-stage larva, and the ensheathed or infective third-stage larva, the reactions of the third-stage larva to heat, cold, light, dryness and chemicals, its ability to remain alive on the ground for long periods, and its habit of climbing on to the herbage in the moisture on its surface. But the study has generally been with a biological bias; little or no attempt has been made to ascertain the relative importance of these points for the development of the diseases under field conditions, and the epidemiological reasons underlying an outbreak of the disease have remained uninvestigated.

The following pages give an account of a little preliminary investigation into the epidemiology of parasitic gastritis, and the results obtained suggest that valuable information may be derived from a further pursuit of this line of enquiry. The histories of the nine outbreaks are set down in a uniform tabular manner to facilitate comparisons and the following of the movements of the sheep, the changing crops and the development of the disease; the periods thought to be particularly dangerous for the acquisition of infection appearing in italics. It will be seen that the information is more complete in some instances than in others, the reason being that the kind of data most useful in this enquiry was not at first appreciated. Following the brief tabular record of the history of each outbreak and notes on the results of autopsies, and other details, appears a brief discussion on the particular outbreak concerned, and the provisional conclusions that may be drawn.

While information derived in this way is, admittedly, less exact than that obtained under experimental conditions, field observations have the advantage that all the various factors concerned in the natural development of the disease are provided for, some of which factors may be unwittingly excluded under the unnatural conditions of a scientific experiment. It is clear that parasitic gastritis is not merely the outcome of a sufficient number of sheep per unit area, grazing there for a sufficient length of time—the product of time and concentration of sheep—but that other factors are of paramount importance; and there is reason to think that this line of investigation may indicate the nature of those factors and their relative significance for the development of an outbreak of the disease.

Outbreak No. 1.

Period	Movements of flock	Remarks
January	Lambing	
March and April	Ewes and lambs penned on kail	*Lambs had been penned over this ground twice during the previous autumn.* The system of penning in the previous year and in the current year had been a good one, lambs not being allowed to run on to ground cleared more than 3 days previously

Notes. Six ewes and forty lambs had died before the outbreak was brought to notice on May 7. Post-mortem examination of a lamb on that date showed 16,000 worms in the stomach, almost entirely *Ostertagia,* and 30,400 in the intestine, almost entirely *Nematodirus.*

At the post-morten examination of a ewe a large number of *Haemonchus* were found, as well as *Ostertagia* and *Nematodirus.*

Observations on Outbreak No. 1.

It is clear that in this instance the heavy infestation of parasites must have resulted from a large number of larvae remaining alive in the soil since the time that the last lot of sheep were penned there.

The reason for the ewe carrying a large number of *Haemonchus* and the lamb being free from that species suggests that *Ostertagia* is able to survive for a longer time in the ground than *Haemonchus.* Experimental observations recently made suggest, however, that that individual lamb might have possessed a natural immunity to *Haemonchus* which would account for the difference.

The observations suggest that:

The infective larvae of *Ostertagia* and *Nematodirus* are able to regain the surface after having been turned in with the plough and survive *en masse* throughout the winter months.

Outbreak No. 2.

Period	Movements of flock	Remarks
Up to September 1	Penned on vetches until disease appeared	210 *lambs had been penned on roots on this ground during the previous autumn and* 100 *had died of parasitic gastritis.* The system of penning the lambs on this crop of vetches was a good one, the lambs being allowed to run over the previous day's and the current day's ground only. Disease broke out here
September 1 to October	Penned on second year clover	This ground had not previously been used for sheep. The lambs were penned wisely but forty had died before September 16, and it was obvious that many more would die

Notes. A post-mortem examination carried out on September 16 (when the height of the epidemic had passed) showed the infection to be almost entirely *Ostertagia.* Only 800 eggs per gram were found on making an examination of a composite sample of faeces. This farmer dosed his sheep regularly with copper sulphate, which may account for the absence of *Haemonchus contortus.*

Observations on Outbreak No. 2.

Although only few particulars are available in connection with this outbreak, they are sufficient to show in a clear way the great danger of penning lambs a second time on the same patch of arable land after too short an interval, and it may be concluded that:

(1) A severe outbreak of ostertagiasis may develop under natural farming conditions without any auto-infestation[1] taking place.

(2) *Ostertagia* larvae may retain their infectivity *en masse* in arable ground for 8 or 10 months.

(3) Deaths may continue to take place for more than 2 weeks after the diseased lambs have been removed from the site of re-infestation.

Outbreak No. 3.

Period	Movements of flock	Remarks
February 21 to April 14, 1931	In lambing pen	Straw strewn on the floor. No herbage to graze
April 14 to May 3, 1931	Penned on rye	*Lambs had been penned here in the spring of* 1930 *and again in August and September* 1930, *the ground had then been ploughed and the rye sown. The system of penning was to allow a small patch of fresh ground each day and to allow the lambs to run over the whole of the cleared ground. Half of this field had already been cleared by flock A (see notes), penned according to the same dangerous system, and the lambs in flock B (in which the disease occurred) were allowed to run over this ground as well as that which they had cleared*
May 3 to June 1, 1931	Penned on rape and turnips	*Lambs had been penned on this ground in May and June* 1930. Deaths began here; three died in the first week, ten in the second, ten in the third and fifteen in the fourth
June 1, 1931	Penned on rye	Sheep had not grazed on this ground in the previous year. Deaths still occurring

Notes. The ewes and lambs were divided into two flocks at the end of March, flock A being composed of strong, single lambs and ewes, receiving concentrated food only once daily, and flock B of twin lambs and ewes, receiving concentrated foods twice daily. Flock A left the lambing pen first (first week in February) and was penned on half of the field of rye where, 2 weeks later, they were followed by flock B. The second half of the crop of rye was given piecemeal to flock B, but these lambs were allowed to run over all of that part of the field previously cleared by flock A. A post-mortem examination made May 29 showed a heavy infestation of *Ostertagia*. Examination of a composite sample of faeces showed a count of 1500 eggs per gram.

Observations on Outbreak No. 3.

An interesting feature of this outbreak is the observation that, although both flocks of lambs were penned on the same crop in the same field, parasitic gastritis only appeared in those which were receiving most concentrated food.

Flock A came direct from the lambing pen to the field of rye and so would be comparatively free from infection. As the worms do not reach maturity and begin to lay eggs in less than 3 weeks and this flock was only penned on the rye for 2 weeks, it is unlikely that flock A greatly increased the infection in the field.

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[1] "Auto-infestation" is used to denote the infestation which originates from eggs disseminated by the particular lambs themselves, as distinct from "residual" infestation, from larvae already present in the soil.

The only explanation which can be suggested, other than an increase of the infestation by flock A, is that the intensity of infection was very different in different parts of the field of rye, and that flock A grazed a part which carried comparatively few larvae, and flock B grazed where there were many. This might have resulted from the weather conditions being particularly suitable for larval development when sheep were last on the ground grazed by flock B, or—and this explanation appears to be the more likely—that during the previous year infestation of the lambs penned in the field greatly increased as they moved across from one side to the other, so that a comparatively light residual infection was left on the part grazed by flock A and a heavy one on the part grazed by flock B.

It may be tentatively concluded that:

(1) Lambs may suffer from acute ostertagiasis when only 9 to 10 weeks old.

(2) The residual infection left where lambs have been penned may be very different in different parts of the field.

(3) An extra allowance of concentrated food is no safeguard against the disease when the rate of infestation is high.

Outbreak No. 4.

Period	Movements of flock	Remarks
February 20 to April 20	Lambing	In bare pen, on straw bedding
April 20 to May 12	Ewes and lambs penned on rape and turnips	*Lambs had been penned on this ground in June of the previous year. During the current year the conditions were very wet and lambs were allowed to run back over a lot of ground.* Lambs began to lose condition here
May 12 to 26	Ewes and lambs penned on permanent pasture	Lambs were penned on this ground in September of the previous year. Symptoms became more marked as soon as the lambs were placed here in the current year and six died
May 26	Penned on winter barley	This ground had not been used by sheep for 2 years. Most of the lambs recovered here

Notes. At a post-mortem examination of a lamb carried out in the first week of June, 4080 *Ostertagia* were collected from the fourth stomach. A composite egg count showed the lambs to be disseminating only 700 eggs per gram. The farmer stated that during April the ground had been very wet and the lambs trampled it into the consistency of porridge, and that there was no growth of vegetation of any kind after the crop had been cleared. After the middle of May most of the lambs made a rapid recovery and on June 14, with the exception of a few very weak ones, were in good condition.

Observations on Outbreak No. 4.

The cause of this outbreak apparently lay in the interval of 10 months between the two successive pennings on the same piece of ground being insufficient to allow for the death of the larvae. The lambs being allowed to run back on to the ground which they had cleared some days previously may, however, also have played a part.

The heavy infestation leading to the deaths which occurred as soon as the lambs were placed on the permanent pasture must be referred to the previous grazing period; and their subsequent recovery to the absence of heavy infestation in the permanent pasture, in spite of this having been grazed by lambs only 8 months previously.

These observations suggest that:

(1) A heavy residual infestation of *Ostertagia* larvae may retain its infectivity in arable ground for 10 months.

(2) Permanent pasture is less dangerous than arable land either for the mass development of the infective larvae, or the longevity of the infective larvae, or for both of these.

Outbreak No. 5.

Period	Movements of flock	Remarks
February 20 to April 7	Lambing	In bare pen bedded with straw
April 7 to May 1	Ewes and lambs penned on 5 acres of rape and turnips in field A	This ground had carried no sheep for the previous 3 years. The ewes were in poor condition and were dosed for worms while on this ground
May 1 to 15	Ewes and lambs penned on rape and turnips	Lambs had been penned on this ground during April and May of the previous year
Mid-May to mid-June	Ewes and lambs penned on winter barley	This ground had carried no sheep for 3 years
Mid-June to mid-July	Lambs weaned and placed on 6 acres of winter tares	This ground had carried no sheep for 3 years. Up to the time they left this crop the lambs had progressed exceptionally well
Mid-July to August 15	Lambs penned on 5 acres of tares on field A	*These same lambs had been penned along with the ewes on this ground April 7 to May* 1. Towards the second week in August symptoms of parasitic gastritis appeared and three died before the flock was moved
August 15 to 26	Lambs penned on spring tares	Lambs had been penned on this ground in July and August of the previous year. Many lambs died here, three, four, seven, eight, ten, and as many as twelve daily

Notes. A post-mortem examination carried out on August 18 showed 16,300 worms in the stomach almost entirely *Ostertagia*, and 56,000 worms in the intestine, mostly *Nematodirus* and *Trichostrongylus*. A large number of these worms were immature and the egg count in the faeces was found to be only 1200 per gram. A second post-mortem examination, carried out on August 26, showed 5900 adult worms and 100 third-stage larvae in the stomach and 48,200 adults in the intestine. Samples of twenty ewes' faeces showed an average count of only 700 eggs per gram. The system of penning practised in each field was that of allowing the lambs only to run over ground which had been cleared 3 or 4 days previously and no more.

Observations on Outbreak No. 5.

The pathogenic infestation in this instance is obviously referable to the double folding over field A. Apparently the heavy infestation there must be attributed to the ewes, as the lambs had not previously had the opportunity of becoming infected to any appreciable extent.

Ewes rarely disseminate eggs in large numbers, and in August these particular ewes were disseminating no more than the usual number, but as they were in poor condition in April and May there seems to be some possibility that they were disseminating more at that time.

The following provisional conclusions may be drawn:

(1) Ewes may carry a sufficiently heavy infestation to leave enough larvae on arable ground to cause disease in lambs, without the necessity for the lambs to reinfect themselves. Or, alternatively, the conditions for larval development where sheep are penned on arable ground may be so favourable that even ewes may leave a dangerous residue of infective larvae.

(2) It is possible for a severe outbreak of ostertagiasis to develop from residual soil infection alone in as short a time as 4 weeks.

(3) The finding of larvae at post-mortem examination on August 26 suggests that their infectivity may be retained for 12 months on arable ground. The inhibition of larval development which is known sometimes to occur must not, however, be overlooked as a possible explanation of this observation.

Outbreak No. 6.

Period	Movements of flock	Remarks
March to June 11	In lambing pen and on permanent pasture	This pasture had been kept as free from sheep as possible between the previous lambing season and the time of its use in the current year
June 11 to 29	Lambs weaned and penned on trefoil	*Lambs had been penned on this ground at some time during the previous year. The system of penning practised was to enlarge the pen by enclosing a patch of the crop each day for 7 days, and then to fence off the ground already cleared and allow the pen to increase in size for another 7 days.* The first death occurred on June 15 and six other lambs died before they were moved from this ground
June 29 to July 27	Penned on oats and tares	This ground had not carried sheep for 2 years previously. *The same system of penning was practised as on the trefoil.* The cake ration was increased but deaths continued. Two occurred in the first week, two in the second, six in the third and sixteen in the fourth weeks on this crop
July 27 to September 21	Penned on second-crop clover	This ground had not carried sheep for 2 years previously. *The same system of penning was again practised* and deaths still continued. Twenty died in the first week, six in the second, then eight, four, ten, six and two during the remainder of the time

Notes. From weaning time onwards the good ram lambs were kept separate from the remainder and received extra cake, but the same treatment as the rest in every other way; these ram lambs receiving extra concentrates remained comparatively healthy and only two died, the other eighty-seven deaths all occurred in the flock receiving the smaller ration of cake. As a result of the exceptionally dry weather the pasture grazed by the ewes and lambs up to June 11 was very bare, barer than had previously been observed in 20 years' experience of sheep farming there.

Observations on Outbreak No. 6.

This outbreak appears to have been caused chiefly by the bad system of penning, but cannot have been due entirely to that, as deaths began to occur only 4 days after the lambs were first penned on the trefoil.

For the same reason it cannot be explained on the grounds of heavy infection remaining in the ground from the folding there during the previous year. The only remaining explanation is that the lambs acquired a heavy infestation on the pasture, and that this was greatly increased by the bad system of penning.

The following conclusions may be drawn:

(1) Very bare pastures are a danger, the condition there being optimum for the acquisition of the larvae by the sheep.

(2) Seven days is ample time for a mass development of infective larvae where sheep are penned on arable ground.

(3) An extra ration of concentrated food is in certain circumstances enough to prevent the development of disease. But extra concentrates cannot cure the disease when once it has appeared, although the rate of infestation may only be such that the development of disease could have been prevented in the first place by extra concentrates.

Outbreak No. 7.

Period	Movements of flock	Remarks
February and March	Lambing on permanent pasture	
Mid-April to end of May	Lambs weaned and penned on 30 acres of clover	*The pens were not closed in behind, the lambs being allowed to run over all the ground which they had cleared*
End of May to early July	Placed on meadow where there had been no sheep for 10 months	Disease broke out here. The lambs were dosed with copper sulphate, and appeared to be cured
Early July to August 1	Penned on vetches	There had been no sheep on this ground for 18 months. *The lambs were allowed to run over all the ground which they had cleared*
August and September	Penned on roots	There had been no sheep on this ground for 18 months. *The lambs were again allowed to run over all the ground which they had cleared.* Disease broke out again here

Notes. Examination of a composite sample of faeces collected on September 15 showed 9750 eggs per gram. A post-mortem examination made on the same date showed a heavy infestation to be present, the majority of the worms being *Haemonchus* but *Ostertagia* were also present. Only twelve lambs had actually died, although the greater part of the flock had suffered severely.

Observations on Outbreak No. 7.

The mass increase of parasites is again seen to have been the result of allowing lambs to run over ground already cleared. The break of 4 or 5 weeks, when the lambs were placed on comparatively clean meadow, removed them from the site of heavy re-infestation and the outbreak appeared to be over. The disease reappeared, however, when they were returned to bad penning conditions, although the ground on to which they were placed was, presumably, quite free from infection. These observations show that:

(1) Penning conditions on arable ground are much more conducive to the mass increase of the parasitic worms than are the conditions of free range on ordinary pasture.

(2) Lambs which make a recovery from parasitic gastritis at 8–12 weeks old are still susceptible to another attack if the intake of infective larvae is increased a few weeks later.

Outbreak No. 8.

Period	Movements of flock	Remarks
February 20 to end of March	Lambing	In pen on arable ground
April to first week of August	Ewes and lambs on new temporary lay (first year)	The ewes and lambs were not penned on the temporary lay (mostly red clover), but were frequently moved from field to field. The year of this outbreak was a wet one, and there was much more herbage than the ewes and lambs could eat; in many fields it was long enough to make into hay
First week of August to first week of October	Lambs weaned and placed on 2nd crop of clover	This land had not been grazed by sheep since the previous autumn, when ewes ran over the stubble for 7–14 days. Lambs received concentrated food from now on. *Lambs were allowed about 1 acre of the crop at a time but allowed to run back over the whole of the ground that had been cleared.* This crop was also very long and there was much more than the lambs could possibly eat
First week of October to end of December	Placed on turnips	*Lambs folded in the same way as on the second-crop clover.* There had been no sheep on this ground for 2 years previously. Deaths occurred here from the first week of October up to the first week of December. Eighty-nine lambs died in all

Notes. Post-mortem examination showed there to be a heavy and almost pure infestation of *Ostertagia.* This farmer made a regular practice of dosing with copper sulphate throughout the summer months, which probably accounts for the absence of *Haemonchus.* It was ascertained on enquiry that the same number of sheep were farmed in the same way in 1929 and grew remarkably well, although the weather was exceptionally dry that year and the ground very bare. This farmer has had some losses from parasitic gastritis in the autumn of most years and considered the freedom from disease in 1929 to be exceptional.

Observations on Outbreak No. 8.

The outstanding feature of this outbreak is that it occurred on ground where the herbage was good, and so plentiful that the lambs were only able to eat a part of it. There is also an interesting history of a previous dry year with approximately the same number of sheep on the same land, when the lambs thrived particularly well. It therefore appears that wet ground and long herbage, which may be thought to constitute optimum conditions for larval development, are more important for the development of the disease than a shortage of herbage, where conditions are presumably optimum for the acquiring of larvae by the sheep.

The enquiry into this outbreak shows that:

(1) Abundance of herbage does not prevent the development of a severe outbreak of ostertagiasis.

(2) Where lambs are folded on arable land, wet weather conditions are much more favourable to the development of *Ostertagia* larvae than dry weather conditions.

(3) Optimum conditions for the larval development of *Ostertagia* are more important than optimum conditions for acquiring infection.

Outbreak No. 9.

Period	Movements of flock	Remarks
June 1931	390 ewes and their lambs penned on vetches	This land had been free from sheep for 12 years previously
July 1931	Ewes and lambs penned on another forage crop	This land had been free from sheep for 8 years previously
August 1931	Lambs weaned. Ewes placed on 12 acres of rape	This land had been free from sheep for 12 years previously
September 1931	Ewes moved on to turnips	*In the previous spring sheep had been penned on kale on this land*
December 25, 1931 to January 30, 1932	Ewes moved on to downland	*During the daytime the* 390 *ewes were confined to a pen of only* 5 *acres*, because of artillery practice over the ground
January 31, 1932 to March 5, 1932	Ewes moved to another piece of downland	Cattle had been on this down, but there had been no sheep since the previous February
March 5, 1932 to April 29, 1932	Ewes moved on to 40 acres of permanent pasture. Lambing commenced, and as it proceeded the ewes and lambs were penned on kale	Ewes had been on this permanent pasture 12 months previously but only for 14 days, after which it had been free from sheep. The ground where the crop of kale was growing had not previously been used for sheep. *The system of penning was to enclose a small patch of fresh kale each day and to allow the sheep to run over the whole of the ground that had been cleared.* Symptoms first appeared on April 23 and several ewes died

Notes. A post-mortem examination revealed a heavy infection of *Haemonchus*. A composite sample of faeces taken from twelve ewes showed 3100 eggs per gram to be present. The ewes with twin lambs had been kept separate from the others and it so happened that for reasons of convenience the cleared land whereon they had been allowed to run had been restricted; although these ewes were also obviously affected, none actually died. None of the lambs showed symptoms of parasitic gastritis at any time.

Observations on Outbreak No. 9.

This again shows with what great rapidity an epidemic may develop where sheep are folded on arable ground and not prevented from wandering on to that part which they have cleared some days previously. The comparison between the results of 6 weeks' grazing on this ground and those of 5 or 6 weeks' grazing on the downland (December 25 to January 30), when 390 ewes were confined to 5 acres during each night, also suggests very strongly that a much greater percentage of the larvae succeeds in reaching the infective stage on arable than they do on pasture.

It might be suggested that the difference in the temperatures in December, and March and April would explain the great difference in the infectivity of the crowded downland pen and the pen on the arable land, but meteorological records show the mean monthly temperature for March to have been 40·5° F., which is 2·4° lower than that for January, and the mean for April only 3·1° higher than the January mean, so that that explanation does not hold.

It may be concluded that:

(1) Severe haemonchosis can develop within 6–7 weeks in previously healthy ewes, feeding on clean arable land.

(2) The conditions of the soil where sheep are penned on arable land are particularly suited to larval development.

(3) Where conditions are otherwise suitable for the development of haemonchosis, it is not necessary for any residual infestation to be present in the soil.

(4) Lambs up to 7 weeks old are not susceptible to the disease, probably because they do little grazing up to that age.

DISCUSSION.

Although field observations such as these do not give the exact kind of information to be derived from actual experiments, they have a very definite place in the investigation of helminthic disease.

The conditions leading up to outbreaks of the diseases caused by parasitic worms in grazing animals are much more complicated than those leading to outbreaks of bacterial disease, resultant upon the requirement of the helminths to pass through a non-parasitic cycle of development. Soil, season, weather, conditions of folding or pasturing, system of cropping, and possibly the kind of crop, are all complicating factors which either do not enter at all into the epidemiology of bacterial diseases or only do so to a slight extent.

Laboratory investigations on the bionomics of the parasites are indispensable in elucidating the various phases of their development and suggesting means of control; but supplementary field enquiries into the epidemiological reasons underlying the mass increase of the parasites are none the less important for the proper understanding of the disease. Valuable information is to be derived from enquiries of this kind as to the relative importance for disease production of the various factors already known to have an influence on the development of the parasite.

Two types of outbreaks of parasitic gastritis.

It is seen from the present brief enquiry here reported that parasitic gastritis may be divided epidemiologically into two main types: firstly, the type of outbreak dependent upon a heavy residual infection in the ground, where the mass increase of parasites in the sheep results from the acquisition of larvae already present in the soil; increase of parasites by auto-infestation not being necessary; and secondly, where residual infection in the ground need not be present, the increase of parasites in the sheep resulting entirely from the acquisition of larvae which have developed from eggs disseminated by those sheep, *i.e.* an auto-infestation.

The two types not infrequently occur quite distinct from one another. The first type, "residual infection," appears in general to be the more acute, it may occur in lambs as young as 9–10 weeks; it is confined to arable land and particularly concerns *Ostertagia*; *Haemonchus* apparently being less able to retain its vitality in the soil. This type of outbreak cannot be checked by any system of penning, but can be avoided if the lambs are not run a second time over the same ground after the lapse of too short an interval.

The second type, "auto-infection," is usually less acute, and takes longer to develop; it is the type seen in lambs on permanent pasture towards the end of the summer, and does not occur in young lambs. At times, however, when sheep are penned dangerously on arable land (allowed to run back on to ground cleared several days previously) and conditions are ideal for larval development, it may appear suddenly and be very acute.

The soil conditions where lambs are penned on arable ground are evidently very much more favourable for larval development than those existing where the lambs are allowed to roam over the whole of a pasture. The most probable explanation for this being that under the crowded conditions of folding, the faeces become well mixed with the soil through the continual trampling, a process which is considerably assisted by the loose nature of the soil on arable land. It is well known that cultures of hookworm larvae develop much more satisfactorily in a mixture of half soil and half faeces than they do in faeces alone, and there is every reason to suppose that the unusually favourable circumstances for larval development which may obtain under penning conditions (such as occurred in outbreak No. 5, where ewes alone left a heavy residual infestation) can be accounted for in this way.

Instances frequently occur, however, of sheep being penned over one and the same patch of ground after only a short interval without any bad result, suggesting that the explanation which has been given is not a complete one and that there are other factors exerting a marked influence on larval development.

Age of susceptibility of lambs.

Enquiry shows that outbreaks occur at different seasons in different parts of the country. August and September is the usual time for this country generally, but in the Eastern Counties its particular season appears to be October and November; in parts of the Midlands outbreaks occur in May and June, and in Wiltshire, Dorset and Hampshire, early spring is the worst time of the year. It is probable that the deciding factor lies, not in the age of the lambs, but the system of farming.

The few observations here recorded show the very different seasons of the year at which these nine outbreaks occurred and give a little information on the earliest age of susceptibility of lambs. Outbreak No. 3 shows that lambs of only 9 or 10 weeks old may suffer severely from parasitic gastritis, where the ground carries a heavy residual infestation of *Ostertagia*; and outbreak No. 9 shows that lambs are immune from haemonchosis up to the age of 7 weeks, presumably because up to that age they do not graze sufficiently to acquire a pathogenic infection.

Time required for the development of an outbreak.

This also is closely associated with the kind of farming. Where the concentration of ewes and lambs at pasture is sufficiently high and they are managed in the same way from year to year, there is a tendency for the disease to appear at the end of the summer, 4, 5 or 6 months being necessary for sufficient increase of parasites to take place through auto-infestation. This tendency has led to the supposition that the increase of parasites is always a gradual process of the accumulation of infection on the ground and in the sheep, spreading itself over months, or even years, as mentioned by Taylor (1929) and again by Morgan (1933). Where residual soil infestation is concerned, this theory of gradually accumulating infection naturally does not hold, but the theory also appears to be open to doubt where outbreaks of disease result from auto-infestation. As seen in outbreak No. 9, severe haemonchosis may develop after only 6–7 weeks of auto-infestation; and outbreak No. 8 suggests that 8 or 9 weeks may be sufficient for the development of ostertagiasis.

The possible importance of the slow accumulation of infection in the development of the disease on permanent pasture cannot be altogether discounted, but the speedy development of disease which follows on the occurrence of optimum conditions for larval development suggests these conditions to be a factor of greater importance. Although we know much of what may influence larval development in the laboratory, we are still very ignorant of the operation of those factors under field conditions and their relative importance in the development of disease.

Effect of nutrition.

Good feeding is, doubtless, of importance in warding off an outbreak of parasitic gastritis. Ross and Graham (1932), Belschner and Edgar (1933) and Edgar (1933) stress the importance of good feeding for the control of the smaller trichostrongyles, and there are several reports of an increase of susceptibility to parasitic worms resulting from inadequate or deficient diet. The observations in outbreak No. 6 are of interest in this connection. The additional supply of concentrated food allowed to some of the lambs concerned in that outbreak appears to have made all the difference between health and disease, either by reducing their grazing period or by assisting their natural powers of resistance.

The history of outbreak No. 3, however, demonstrates the futility of extra feeding where infestation is high. In this instance the lambs which received double the amount of concentrated food contracted the disease and the others remained healthy; the extra infection to which the diseased lambs were subjected evidently being too great to be counteracted by the extra amount of concentrated food.

That good feeding is no safeguard where the rate of infection is high is also clearly shown in outbreak No. 8, where, although there was more herbage than the lambs could possibly eat, a particularly severe outbreak of ostertagiasis occurred.

Rate of increase of soil infection.

The differences in the suitability of various soils or various conditions of the soil for the culture of the larvae have been mentioned as of great importance in the development of an outbreak of parasitic gastritis.

Ostertagia appears to be much more difficult than *Haemonchus* to culture in the laboratory, and this factor of suitability for larval growth may be of particular importance where outbreaks of ostertagiasis are concerned.

The residual infection in the ewes is not generally considered to be of any great consequence, observations on twelve ewes on heavily infected pasture having shown that at no time did they disseminate more than 700 eggs per gram of faeces. The observations on outbreak No. 5 clearly show, however, that, where exceptionally favourable conditions for larval development exist, the ewes may disseminate sufficient eggs to leave a very heavy infection in the soil.

This observation also emphasises how small a percentage of the eggs of these worms usually reach the infective larval stage. If it is possible for ewes to leave such a heavy infection as was observed in this outbreak, after having been on the ground for only four days, it is clear that the differences between the efficiency of larval development as it occurs under various natural conditions must be enormous.

Time required for development of infective larva under field conditions.

Interesting observations are also made on the time required for the development of the infective larva under actual field conditions.

A fair amount of information is to be found in the literature as to the temperatures required for larval development under laboratory conditions; and it has been thought that 10 days might be taken as the average time required for the completion of larval development under field conditions during the summer months (Stoll, 1932; Taylor, 1929). The evidence obtained in outbreak No. 6, however, clearly shows that larvae may reach the infective stage in less than 7 days in sufficient numbers to cause a particularly acute outbreak of ostertagiasis.

Survival of infective larvae in the soil.

Good evidence has been obtained on this point. Outbreaks Nos. 1, 2, 3 and 4 show that the infective larvae of *Ostertagia* may regain the surface after having been buried by the plough, and survive in disease-producing numbers for 8 to 10 months. The finding of third stage larvae in one lamb in outbreak No. 5 suggests that some *Ostertagia* larvae may even survive up to 12 months: in the interpretation of this instance, however, the possibility must not be overlooked of the growth of young larvae in the host being inhibited for a time, as has been observed by Scott (1928) in hookworms in dogs. The circumstances of the finding of *Haemonchus* in ewes and not in lambs in outbreak No. 1 suggests that this species does not survive so well as *Ostertagia* and *Nematodirus*.

The type of outbreak resulting from a residual soil infestation does not appear to take place on permanent pasture, and it is clear that larvae survive more successfully on arable ground.

CONCLUSIONS.

1. There are two epidemiological types of parasitic gastritis:

(*a*) Where pathogenic infestation is acquired from a residue of infective larvae present on the land.

(*b*) Where pathogenic infestation is acquired as a result of auto-infestation.

2. Infective larvae of *Ostertagia* can regain the surface of the soil after being turned in by the plough, and retain their infectivity for 8–10 months in sufficient numbers to cause severe disease.

3. *Nematodirus* larvae can regain the surface after being turned in by the plough, and retain their infectivity *en masse* throughout the winter months.

4. Severe haemonchosis can develop by auto-infestation alone, on clean arable land, in as short a time as 7 weeks.

5. Severe ostertagiasis can develop from residual soil infestation alone, in as short a time as 4 weeks.

6. The residue of infective larvae where sheep have been penned over a field may be very different in different parts of the field.

7. Lambs up to 7 weeks old are not susceptible to haemonchosis under natural farming conditions.

8. Lambs as young as 9 or 10 weeks old may suffer from severe ostertagiasis under farming conditions.

9. Conditions may be so favourable for larval development on arable land that even the relatively small number of eggs disseminated by ewes may be sufficient to leave a dangerous infection in the soil after once penning over.

10. Six days is sufficient for the mass development of infective larvae under actual field conditions.

11. Bare pastures are a danger as conditions are then optimum for the acquisition of the larvae.

12. Grazing where there is abundance of herbage (clover), to such an extent that the lambs cannot eat more than half of the crop (representing a minimum acquisition of infective larvae by grazing), does not safeguard against the development of ostertagiasis on arable land.

13. There is an enormous difference between the suitabilities of various field conditions for larval development. The risk of pathogenic infection is much greater on arable land where precautions are not strictly observed, than it is on permanent pasture.

14. An extra supply of concentrated food is sufficient to ward off an outbreak of the disease where the rate of infestation only reaches a certain level, but where infestation is high, a plentiful supply of concentrated food does not prevent the development of a severe outbreak.

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SOME FACTORS INFLUENCING LODGING IN CEREALS.

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Lodging in cereals is a problem which has attracted attention for more than a century. As early as 1798 Sir Humphry Davy(1)[1] associated lodging with a low silica content of the straw, but, as was characteristic of the time, his views were based principally on speculation. In 1842 Liebig(2) also attributed lodging to a deficiency of silicon. The importance of silicon was emphasised also by Kuhn(3), Swiecicki(4), and recently by Davidson and Phillips(5). The latter investigators found that the silica and ash content in the straw from a lodged plot was in every case lower than from the control. They also point out that the lignin content of the straw from the lodged plot was distinctly higher in every case than from the control and accordingly suggest that, should the cause of lodging be sought in lignin-content variations between lodged and erect plants, the conclusion would have to be reached that high and not low lignin content is the cause of lodging.

As a result of the work of Sachs(6), Knop(7), Jodin(8), Mayer(9), and others, the importance of silica from the viewpoint of straw strength seems to have fallen into disrepute because plants have been found to make apparently normal growth, even to maturity, in nutrient solutions free from silicic acid.

Kraus (10, 11, 12) carefully analysed the morphological aspect of the problem and came to the conclusion that it was not possible to find any one factor that can be used as an index of standing power. Zade(13) concluded that stiffness of straw is not an adequate guide to resistance to lodging, and points out that a stiff straw is of little use if the root system is weak. He regards length of straw and leaf area as important factors, and the resistance to bending of the stem as the best measure of standing power.

Draghetti(14) found as a result of his investigations that the flexibility of the first internode is directly correlated with the degree of resistance to lodging.

Zavada(15), working with barley, came to the conclusion that neither the deductive method, based on measurements and weighings, nor the direct determination of resistance calculated as absolute strength, leads to useful results. He bases his reasons for this statement on the fact that resistance to lodging is not only dependent on culm strength but also on culm elasticity besides other factors, including the number and arrangement of the leaves.

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[1] (1) Literature cited.

Lange(16) found that standing power in wheat was associated with short stiff straw and poor tillering potentiality.

Welton and Morris(17) assert that lodging is due to the interaction of many factors, both environmental and hereditary, and maintain that whenever the interaction of these factors results in the development of a relatively low dry-matter content per unit length of culm, lodging occurs.

Tubbs(18) studied the effect of manurial deficiency upon the mechanical strength of barley straw. His investigations show that the strength of succeeding internodes of fully manured plants falls off rapidly. Nitrogen and phosphorus deficiency result in a large increase in strength of the lower internodes, while potassium starvation decreases the strength of the lower and increases that of the middle internodes. The effects of manurial deficiency were most marked in the lower internodes, the upper ones approximating to the normal. The variation in the thickness of the mechanical tissues follows that of strength, but is not sufficient to account for the large differences observed. Accordingly, Tubbs concludes that the observed reduction in the strength of succeeding internodes from below upwards, is due both to a decrease in the efficiency of the mechanical tissues and also to a decrease in their actual amount. Moreover, he suggests that the observed effects of mineral deficiency are explicable on the assumption that potassium is essential to the production of an efficient mechanical tissue.

Kraus(10) and Willis(19) have each described apparatus for measuring the strength of straw apart from its roots. Studtmann(20) has devised an apparatus which measures the resistance of the whole plant while it is still growing.

Moldenhawer(21), working with wheat and barley, found the number of vascular bundles to be a distinguishing characteristic for different varieties and concluded that non-lodging forms could be selected by means of the number of vascular bundles. In general the lodging resistant forms contained the greater number of vascular bundles.

Garber and Olson(22) studied lodging from the morphological aspect and concluded that in oats, resistance to lodging was associated with thickness of sclerenchyma cell wall. Working with barley, the same investigators found that there was no consistent correlation between thickness of sclerenchyma cell wall and ability to resist lodging.

Considering the diversity of views expressed by the various investigators as to what constitutes resistance to lodging in cereals, it is not surprising to find that the literature directly concerned with the inheritance of standing power is scarce. Indeed what has been done in this direction is only of an empirical nature.

Howard and Howard(23) recognised that the character for stiff straw must be combined with a strong root system in a wheat which was to be resistant to lodging and they successfully produced a hybrid with these two heritable qualities.

Nilsson-Ehle, cited by Tschermak(24), found transgressive segregation when breeding wheat for strong straw and obtained easily lodged forms from the hybridisation of two resistant varieties. Berg(25) also found transgressive segregation in straw stiffness among the progeny of a cross between the fairly stiff-strawed gold barley and an early six-rowed, weak-strawed variety.

In Saorstat Eireann much success has been achieved in the production of strong-strawed varieties of oats and wheat. Generally speaking, Irish soil is fertile and the rainfall during the growing period abundant. These conditions favour luxuriant growth and consequently are conducive to lodging. Hence, the combining of lodging resistance with other desirable characteristics must always remain an important aim in the production of varieties suitable for cultivation in this country. In 1932 work was commenced at the Albert Agricultural College, Glasnevin, with a view to determining if any simple morphological character of the plant is closely associated with lodging. If such a criterion of sufficient reliability could be found, it would enable the early isolation of lodging resistant strains and would thus greatly facilitate breeding work.

MATERIALS AND METHODS.

As a starting-point three varieties were chosen which experience has shown to display varying degrees of resistance to lodging. The varieties referred to are Glasnevin Sonas, which is highly resistant to lodging; Sandy, which is easily lodged; and Victory II, which is intermediate in this respect. In order to give the experiment a wider inductive basis each variety was grown at three different spacings, namely 4 in., 6 in. and 8 in. between the rows. The distance apart of the plants in the rows was in all cases 2 in. The nine combinations resulting from the use of three varieties and three spacings were arranged in a 9 × 9 Latin square. The arrangement of the plots was as follows:

1	9	8	4	2	7	3	6	5
9	3	6	8	4	1	5	2	7
8	4	7	5	6	9	2	1	3
6	5	4	1	9	3	8	7	2
7	8	3	2	5	6	4	9	1
3	2	9	6	7	5	1	4	8
2	6	5	7	1	8	9	3	4
5	1	2	9	3	4	7	8	6
4	7	1	3	8	2	6	5	9

		Variety	Spacing
1	equals	Victory II	4 in.
2	,,	Sandy	4 ,,
3	,,	Sandy	6 ,,
4	,,	Glasnevin Sonas	6 ,,
5	,,	Victory II	6 ,,
6	,,	Glasnevin Sonas	8 ,,
7	,,	Glasnevin Sonas	4 ,,
8	,,	Victory II	8 ,,
9	,,	Sandy	8 ,,

The dimensions of each plot were 5 ft. × 5 ft. 9 in. The area on which observations were made was 1 sq. yd. centrally situated in each plot. The plots were contiguous in the rows, but each row of nine plots was separated from the next row by a path 1 ft. 6 in. wide.

The vegetative tillering capacity of each variety was determined by selecting at random one row in each plot and counting the number of plants and tillers in it. The average figure recorded for each plot was based on counts of from thirteen to eighteen plants. This method was found to give the same average result as counting the whole plot, and being less laborious was adopted. The fact that both methods tended to give the same result was undoubtedly due to the uniform spacing. The number of ear-bearing tillers for each variety was determined by counting the total number of plants and ears in each plot at harvest.

For the determination of height, diameter of stem, length of internode, etc., five plants were selected at random from each plot. Two sets of samples were taken, one after ear emergence and the other at harvest time. The samples taken at harvest time were used for external measurements alone. The samples taken after ear emergence were used to furnish data on internal anatomy. In view of the possibility of correlation between any external and internal measurements, it was considered desirable also to make external measurements on these plants. The samples were taken on different dates for each variety in order to have each sample at the same morphological stage of development.

The lengths of the internodes on the main culm of each plant were measured. The diameter of the fifth internode (internodes numbered from above downwards, *i.e.* internode under ear was No. 1) was also measured by means of a micrometer screw. The figure recorded for each culm was obtained by taking the mean of two diameters measured at right angles at the same point on the culm. A small piece was then cut from the centre of the fifth internode and put in a bottle containing formalin acetic alcohol. The bottle was labelled with the plot number and the contents reserved for sectioning. The fifth internode was selected for detailed study, because preliminary examination of a large number of lodged culms showed that in the great majority of cases lodging was due to fracture of the fifth or sixth internode. The sixth internode was not selected because, in the case of Glasnevin Sonas, this internode was so short that it could not be easily measured, nor could a portion be cut from it for sectioning which would be comparable with portions taken from the sixth internode of Sandy and Victory II.

Various methods of obtaining microtome sections, including the celloidin(26), the cellulose acetate(27), and the paraffin method, after pretreatment of the material with hydrofluoric acid, were tried but without sufficient success, due to the extreme hardness of the material. Sections were obtained by the paraffin method, but unfortunately they were unable to supply all the information required due to the partial disintegration of the parenchymatous tissue by the hydrofluoric acid. The minimum concentration of acid necessary to effect sufficient softening of the lignified tissue was injurious to the unlignified tissue. Efforts to get over this difficulty by increasing the time which the acid was allowed to act and decreasing the concentration were unsuccessful. Eventually freehand sections were resorted to. *Entire* cross-sections of the stem were cut as thinly as possible. These were found good enough to supply all the information required with the exception of sclerenchyma cell-wall measurements. For the latter measurements very thin *partial* sections were cut and found to be satisfactory. The *entire* cross-sections, used to supply the larger dimensioned data, were stained in chlor-zinc iodine. This material stained lignified elements yellow and cellulose walls blue.

The partial sections, used for cell-wall measurements, were stained in safranin.

The anatomical data taken were as follows: width of culm wall, width of lignified tissue (sclerenchyma plus lignified parenchyma), width of thick-walled tissue (sclerenchyma plus collenchyma), number of vascular bundles and thickness of sclerenchymatous cell walls. For width of culm wall, lignified tissue, etc., ten measurements were made on each section and the mean taken. For thickness of sclerenchyma cell walls the measurements were made from cavity to cavity of the cell. Fifteen measurements were made on each section and half the mean taken as the cell-wall thickness. All measurements were made under the microscope with a micrometer eyepiece. An oil immersion lens was used for the sclerenchyma cell-wall measurements.

GENERAL OBSERVATIONS.

The experimental plots were sown on March 15 and 16 and the plants were visible over ground on April 7. The growth of Victory II was faster than that of Sandy or Sonas. The establishment for each variety was good, but Sandy was superior in this respect to either Victory II or Sonas. In the early stages, Sandy exhibited a prostrate habit of growth which stood out in sharp contrast with the erect habit of Sonas and Victory II. Throughout the greater part of the growing season the growth rate of Sandy and Victory II was more rapid than that of Sonas. However, from the commencement of ear emergence onwards, Sonas grew very rapidly and by the end of flowering time occupied an intermediate position with respect to height between Sandy and Victory II.

It may also be pointed out that from the middle of June onwards Sonas presented a rather hard-looking appearance. The leaves were erect and consequently there was much less shading of the lower portions of the stems in this variety than in Victory II or Sandy. In the latter varieties the drooping uppermost leaves meet across the rows and tend to form a canopy which cuts off a considerable amount of light from the basal parts of the stems. Erectness of the leaves in Sonas is, however, a characteristic which is influenced by soil fertility. When the fertility reaches a certain level the growth habit of Sonas is similar to Victory II. Nevertheless, it seems as if the degree of fertility which produces a similar effect in both varieties is much higher in the case of Sonas than in Victory II.

Heavy rain which fell on July 13 and 14 caused a good deal of lodging in the plots. The results of observations made afterwards revealed the superior lodging resistance ability of Sonas when compared with the other two varieties. The following is a summary of the observations:

Victory II:	3 plots erect.
	12 plots slightly lodged.
	12 plots badly lodged.
Glasnevin Sonas:	24 plots erect.
	2 plots slightly lodged.
	1 plot badly lodged.
Sandy:	2 plots erect.
	8 plots slightly lodged.
	17 plots badly lodged.

No definite association between spacing and lodging was apparent at this stage.

The plots were harvested on August 23 and 24, and a count made of the number of lodged and erect plants in each plot.

ANALYSIS OF DATA.

Tillering.

A count was made on May 20 to ascertain the tillering capacities of the varieties included in the experiment. The results are shown in Tables I and II.

Table I. *Mean tillering per plant.*

Variety	Mean (27 plots)	Spacing in.	Mean (27 plots)
Glasnevin Sonas	4·59	4	4·52
Victory II	4·08	6	4·69
Sandy	5·40	8	4·86

Table II. *Analysis of variance—tillering.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. × 10)
Rows	8	1·5568	0·1946	—
Columns	8	3·2194	0·4024	—
Variety	2	24·5214	12·2607	2·4045
Spacing	2	1·2860	0·6430	0·9505
Interaction	4	0·6012	0·1503	0·2037
Error	56	7·3808	0·1318	0·1380
Total	80	38·5656		

Z for variety $= 2{\cdot}2665$.
" spacing $= 0{\cdot}7925$.
" interaction $= 0{\cdot}0657$.

The values of Z obtained for variety and spacing are greater than the theoretical values at the 1 and 5 per cent. points respectively, for corresponding degrees of freedom. Hence, it can be said that the varieties tested differ significantly in tillering capacity, and also that the different spacings used in the experiment significantly affect tillering.

Since varietal and spacing effects are significant, the variety and spacing means may be tested to determine which differences are real.

$$\text{Appropriate standard error} = \sqrt{\frac{2 \times \cdot 1318}{27}} = 0{\cdot}0988.$$

A mean difference to be significant must be greater than $t \times$ standard error. The value of t to be used is that corresponding to 56 degrees of freedom. The t table (28) gives values for 30 and ∞ degrees of freedom, so that the value for 56 degrees has to be determined by interpolation. The values thus obtained are 2·0029 for the 5 per cent. point and 2·6664 for the 1 per cent. point.

Calculated mean difference (5 per cent.) = 0·20.
,, ,, (1 per cent.) = 0·26.

A comparison of the observed mean differences with the calculated mean difference, leads to the conclusion that Sandy is superior in tillering capacity to Glasnevin Sonas or Victory II. Glasnevin Sonas is also superior to Victory II.

Eight-inch spacing gives significantly better tillering than 4-in. spacing. The differences between 6-in. and 4-in. and between 8-in. and 6-in. spacings do not reach the required level. Nevertheless, they indicate that there is a steady response in tillering to increased spacing.

Autumn tillering.

The results obtained are presented in Tables III and IV.

Table III. *Mean number of ear-bearing tillers per plant.*

Variety	Mean	Spacing	Mean
Glasnevin Sonas	1·45	4	1·28
Victory II	1·58	6	1·73
Sandy	2·01	8	2·03

Table IV. *Analysis of variance—ear-bearing tillers.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	½ log$_e$ (mean sq. × 100)
Rows	8	1·21	—	—
Columns	8	0·79	—	—
Variety	2	4·72	2·36	2·7319
Spacing	2	7·80	3·90	2·9831
Interaction	4	0·22	—	—
Error	56	2·32	0·0414	0·7104
Total	80	17·06		

Z for variety = 2·0215 (significant).
,, spacing = 2·2727 (significant).
Standard error of difference of two means = 0·056.
Calculated mean difference (5 per cent.) = 0·11.
,, ,, (1 per cent.) = 0·15.

Conclusions. Sandy produces more autumn tillers per plant than Victory II or Sonas. Victory II is also superior to Sonas in this respect.

Six-inch spacing produces more ear-bearing tillers per plant than 4-in. spacing. Eight-inch spacing also produces more than 6-in. spacing.

It is interesting to note that Sonas, which produced more tillers than Victory II in May, is surpassed by the latter variety in the production of autumn tillers. Evidently then, the proportion of tillers which fail to produce ears is higher in Sonas than Victory II.

Yield of grain.

The results obtained are shown in Tables V and VI.

Table V. *Mean yield of grain (gm.).*

Variety	Mean	Spacing in.	Mean
Glasnevin Sonas	346·29	4	321·15
Victory II	300·78	6	321·70
Sandy	250·18	8	254·40

Table VI. *Analysis of variance—yield of grain.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. − 1000)
Rows	8	35777·062	—	—
Columns	8	11492·839	—	—
Variety	2	124820·024	62410·012	2·0669
Spacing	2	80850·839	40425·420	1·8498
Interaction	4	6473·976	1618·494	—
Error	56	138935·655	2480·993	0·4544
Total	80	398350·395		

Z for variety = 1·6125 (significant).
,, spacing = 1·3954 (significant).
Standard error of difference of two means = 13·55.
Calculated mean difference (5 per cent.) = 27·14.
,, ,, (1 per cent.) = 36·13.

Conclusions. Sonas gave a significantly higher yield of grain than Victory II or Sandy. Victory II was superior to Sandy.

Four-inch and 6-in. spacings gave significantly higher yields than 8-in. spacing.

Exception might be taken to these conclusions on the grounds that the extraction of samples from the plots during the growing season would interfere with the yield. The extraction of samples undoubtedly reduced the yield of all three varieties, but, since the experimental lay-out was a balanced one and the same number of plants were taken from each plot, all varieties were equally affected. Hence, the comparability of the results was not interfered with.

Moreover, these varieties have been thoroughly tested in previous yield trials. The results of these trials are in agreement with those obtained in the present experiment, where the comparison of yields was not the main consideration.

Yield of straw.

Sandy gave the highest yield of straw. The yield of Sonas was significantly superior to the yield of Victory II, which is remarkable in view of the fact that both varieties produce straw of about the same length and that Victory II surpasses Sonas in the production of autumn tillers. Evidently Sonas straw is heavier than Victory II straw. This result may be partly due to Victory II being slightly riper than Sonas when harvested. It seems a characteristic of Sonas to preserve, irrespective of degree of ripeness, that turgid appearance of the straw which is only found in the early stages of ripening in most other varieties.

The mean yields were as follows:

Victory II (oz.)	Sonas (oz.)	Sandy (oz.)	Standard error
17·00	18·85	21·41	0·43

Lodging.

At harvest time a count was made of the number of lodged and erect plants in each plot. All plants which departed more than slightly from the erect position were classified as lodged. As the total numbers of plants in the 4-in., 6-in. and 8-in. plots were different, the number of lodged plants in each plot was expressed, for purpose of comparison, as a percentage of the total. The mean percentage lodged is shown in Table VII.

Table VII. *Mean percentage lodged.*

Variety	Mean	Spacing in.	Mean	Standard error of a variety or spacing mean
Sonas	9·8	4	58·4	—
Victory II	76·8	6	62·5	4·89
Sandy	93·4	8	59·2	—

These results show the marked lodging resistance ability of Sonas compared with the other varieties. Spacing, within the limits imposed by this experiment, did not influence the amount of lodging. It cannot be generalised from this result that spacing does not affect lodging. The failure of spacing to do so in this experiment may have been due to insufficient differentiation in plot population.

Length of straw.

The results obtained are presented in Tables VIII and IX.

Table VIII. *Mean length of straw (cm.).*

Variety	Mean	Spacing in.	Mean
Sonas	120·0	4	121·2
Victory II	119·0	6	122·2
Sandy	124·4	8	120·4

Table IX. *Analysis of variance—length of straw.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. $\div$ 10)
Rows	8	1157·210	—	—
Columns	8	683·654	—	—
Variety	2	491·950	245·975	1·6014
Spacing	2	44·765	22·382	—
Interaction	4	75·606	35·303	—
Error	56	1889·358	33·738	0·6081
Total	80	4342·543		

Z for variety = 0·9933 (significant).
Standard error of difference of two means = 1·58.
Calculated mean difference (5 per cent.) = 3·16.
,, ,, (1 per cent.) = 4·21.

Conclusions. Sandy has significantly longer straw than Sonas or Victory II. There is no difference between Sonas and Victory II.

Stem diameter.

The results of measurements made on the fifth internode are shown in Table X.

Table X. *Stem diameter (mm.).*

Variety	Mean	Spacing in.	Mean
Victory II	5·16	4	5·20
Sonas	5·53	6	5·32
Sandy	5·21	8	5·37

Table XI. *Analysis of variance—stem diameter.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. × 100)
Rows	8	1·127	—	—
Columns	8	0·969	—	—
Variety	2	2·269	1·135	2·3659
Spacing	2	0·415	0·208	1·5175
Interaction	4	0·474	0·119	1·2383
Error	56	3·687	0·066	0·9436
Total	80	8·941		

Z for variety = 1·4223 (significant).
,, spacing = 0·5739 (insignificant).
Standard error of difference of two means = 0·07.
Calculated mean difference (5 per cent.) = 0·14.
,, ,, (1 per cent.) = 0·18.

Conclusion. Sonas has significantly greater stem diameter than Sandy or Victory II.

Length of fifth internode.

The measurements for length of fifth internode are presented in Table XII.

Table XII. *Length of fifth internode.*

Variety	Mean	Spacing in.	Mean
Sonas	9·04	4	11·61
Victory II	10·40	6	11·19
Sandy	13·41	8	10·06

Table XIII. *Analysis of variance—length of fifth internode.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq.)
Rows	8	41·898	—	—
Columns	8	63·937	—	—
Variety	2	269·147	134·574	2·4512
Spacing	2	34·858	17·429	1·4291
Interaction	4	25·437	6·359	0·9249
Error	56	101·905	1·819	0·2991
Total	80	537·182		

Z for variety = 2·1521 (significant).
„ spacing = 1·1300 (significant).
„ interaction = 0·6258 (significant).
Standard error of difference of two means (variety or spacing) = 0·367.
„ „ „ (interaction) = 0·636.

Table XIV. *Interaction means.*

Variety	4 in.	6 in.	8 in.
Sonas	9·29	9·50	8·36
Victory II	10·56	10·42	10·23
Sandy	14·99	13·66	11·58

Conclusions. The fifth internode of Sonas is significantly shorter than the fifth internode of Victory II or Sandy. Victory II has a significantly shorter fifth internode than Sandy.

Plants grown at 8-in. spacing have a shorter fifth internode than when grown at 4- or 6-in. spacing.

Spacing does not significantly alter the length of the fifth internode in Victory II or Sonas, whereas in Sandy the difference between each spacing is significant.

Length of fourth internode.

In Sonas this internode is also significantly shorter than in Victory II or Sandy.

The means are:

Sonas	Victory II	Sandy	Standard error
12·18	14·37	14·73	0·25

Thickness of culm wall.

Sonas has a significantly thicker culm wall than Victory II or Sandy. The means are:

Sonas (mm.)	Victory II (mm.)	Sandy (mm.)	Standard error
1·28	1·20	1·19	0·022

The measurements were made in microns and reduced to millimetres.

Number of vascular bundles.

The mean number of vascular bundles as determined for each variety and spacing is shown in Table XV.

Table XV. *Number of vascular bundles.*

Variety	Mean	Spacing in.	Mean
Victory II	50·78	4	56·6
Sonas	64·30	6	58·8
Sandy	60·18	8	59·7

Table XVI. *Analysis of variance—number of vascular bundles.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. ÷10
Rows	8	239·285	—	—
Columns	8	227·062	—	—
Variety	2	2593·359	1296·679	2·4323
Spacing	2	139·580	69·790	0·9715
Interaction	4	5·901	—	—
Error	56	1520·542	27·152	0·4994
Total	80	4725·729		

Z for variety = 1·9329 (significant).
„ spacing = 0·4721 (insignificant).
Standard error of difference of two means = 1·42.
Calculated mean difference (5 per cent.) = 2·84.
„ „ (1 per cent.) = 3·79.

Conclusions. Sonas has significantly more vascular bundles than Sandy. Sandy has significantly more than Victory II. With regard to the distribution of the bundles in the cross-sections, the ratio of the number of bundles towards the periphery, to the number situated in the lignified parenchyma, is practically constant for all three varieties.

Width of lignified tissue.

The mean width of lignified tissue (in microns) is shown in Table XVII.

Table XVII. *Width of lignified tissue.*

Variety	Mean	Spacing in.	Mean
Sonas	518	4	454
Victory II	479	6	495
Sandy	457	8	504

Table XVIII. *Analysis of variance—width of lignified tissue.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. ÷ 1000)
Rows	8	55311·778	—	—
Columns	8	43992·222	—	—
Variety	2	51101·407	25550·704	1·6204
Spacing	2	38500·667	19250·334	1·4788
Interaction	4	2097·282	524·371	—
Error	56	127840·444	2282·8	0·4126
Total	80	318843·800		

Z for variety = 1·2078 (significant).
„ spacing = 1·0662 (significant).
Standard error of difference of two means = 13.
Calculated mean difference (5 per cent.) = 26·03.
„ „ (1 per cent.) = 34·66.

Conclusions. Sonas has significantly more lignified tissue than Victory II or Sandy. There is no difference between Victory II and Sandy.

Six- and 8-in. spacings produce significantly more lignified tissue than 4-in. spacing.

Width of thick-walled tissue (sclerenchyma + collenchyma).

The mean width (in microns) of thick-walled tissue is shown in Table XIX.

Table XIX. *Width of thick-walled tissue.*

Variety	Mean	Spacing in.	Mean
Sonas	117·60	4	102·0
Victory II	110·26	6	108·0
Sandy	91·90	8	109·7

Table XX. *Analysis of variance—width of thick-walled tissue.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. − 100)
Rows	8	3018·667	—	—
Columns	8	1200·223	—	—
Variety	2	9438·000	4719·00	1·9271
Spacing	2	881·445	440·72	0·7416
Interaction	4	182·555	—	—
Error	56	6556·666	117·083	0·0789
Total	80	21277·556		

Z for variety = 1·8482 (significant).
„ spacing = 0·6627 (significant).
Standard error of difference of two means = 2·945.
Calculated mean difference (5 per cent.) = 5·90.
„ „ (1 per cent.) = 7·85.

Conclusions. Sonas has a significantly wider band of thick-walled tissue than Victory II. The latter variety has a much wider band than Sandy.

Six- and 8-in. spacings cause the production of a significantly wider band of thick-walled tissue than 4-in. spacing.

Thickness of sclerenchyma cell wall.

The mean thickness (in microns) of sclerenchyma cell wall is shown in Table XXI.

Table XXI. *Thickness of sclerenchyma cell wall.*

Variety	Mean	Spacing in.	Mean
Sonas	5·12	4	4·34
Victory II	4·71	6	4·69
Sandy	3·87	8	4·67

Table XXII. *Analysis of variance—thickness of sclerenchyma cell wall.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. × 10)
Rows	8	5·3791	—	—
Columns	8	2·9671	—	—
Variety	2	22·0983	11·0491	2·3525
Spacing	2	2·0929	1·0465	1·1743
Interaction	4	0·3647	0·0912	—
Error	56	19·4972	0·3482	0·6238
Total	80	52·3993		

Z for variety = 1·7287 (significant).
„ spacing = 0·5505 (insignificant).
Standard error of a difference of two means = 0·161.
Calculated mean difference (5 per cent.) = 0·32.
„ „ (1 per cent.) = 0·43.

Conclusions. Sonas has significantly thicker sclerenchyma cell walls than Victory II. Victory II has significantly thicker walls than Sandy.

DISCUSSION.

From the data and results presented on the preceding pages it will be seen that Glasnevin Sonas differs significantly from Sandy, and also in many instances from Victory II, with respect to the degree which it possesses those attributes generally associated with strength of straw. The question which now arises is—Do all exceptionally strong strawed varieties possess those attributes to the same or to a greater degree than Glasnevin Sonas, and if so, can any one or a number of these characteristics be taken as providing an absolute criterion of resistance to lodging? The first part of this question must remain unanswered until such time as data are available for a number of other strong strawed varieties. The information obtained during the course of this investigation will provide material for a brief discussion on the second part of the question.

The data already presented show that differential spacing tends in nearly every case to produce differences in the means of the parts measured, and the Analysis of Variance tables show that in a number of instances these differences are significant. In all cases where they are significant the spacing differences show that wide spacing seems to produce the characteristics associated with lodging resistance. The reason that all the mean spacing differences are not significant is very likely due to insufficient range between the spacing limits used.

Evidently, then, differences in density of the plant population are effective in altering the dimensions of some of those attributes studied.

Further evidence of the efficacy of environment in altering the build of oat plants may be obtained from the following observations. A portion of a plot of Glasnevin Sonas was treated with sulphate of ammonia. On July 19 four random samples were taken from the treated and four from the untreated portion of the plot. Measurements were made on each plant for height, length of internode and diameter of stem. The results are shown in Tables XXIII and XXIV.

Table XXIII. *Effect of nitrogen on height, length and diameter of fifth internode.*

	Means	
	Treated	Untreated
Height (cm.)	123	108
Length of fifth internode (cm.)	12·82	8·67
Diameter of fifth internode (mm.)	1·72	1·75

Table XXIV. *Analysis of variance—height.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq. ÷ 10)
Between treatments	1	7084·034	7084·034	3·2816
Between samples	6	739·433	123·239	1·2556
Within samples and between plants	112	5434·000	48·518	0·7897
Total	119	13257·467		

Table XXV. *Analysis of variance—length of fifth internode.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq.)
Between treatments	1	517·920	517·920	3·1249
Between samples	6	34·783	5·797	1·7573
Within samples and between plants	112	153·970	1·3747	0·1593
Total	119	706·673		

Comparing the 6 degrees of freedom with 112 degrees of freedom, $Z = 0·4659$. Since this value of Z is significant, the difference in height, between the means of the treated and untreated plots, cannot be attributed exclusively to the effect of the nitrogenous dressing. Soil heterogeneity caused significant variation in height. A better designed experimental lay-out would be necessary to establish the precise effect of nitrogen.

Comparing the 1 degree of freedom with 6 degrees of freedom, $Z = 1{\cdot}3676$.

Comparing the 6 degrees of freedom with 112 degrees of freedom, $Z = 1{\cdot}5980$. Since the latter value of Z is also significant, the remarks made about Table XXIV must also be applied to Table XXV.

Although it cannot be concluded that the difference in mean length of internode between treated and untreated plots is due to nitrogen alone, it can be taken that length of internode is subject to considerable variation as a result of soil heterogeneity. Length of internode, therefore, is not of any use as an absolute criterion of resistance to lodging.

It is now of interest to know how the histological elements of the plant react to soil variation. No special experiment was designed to elucidate this point last season. However, some information may be deduced from the evidence disclosed by the Latin square experiment.

From an examination of the Analysis of Variance tables presented on the preceding pages it is apparent that for each one of the various attributes analysed a considerable portion of the total variability is accounted for by soil variation between rows and columns in the experimental lay-out. Since the various sets of data have been obtained from the same experiment, the soil variation was the same for each set. Evidently then the external parts of the plant such as height and length of internode are affected to a greater extent by soil heterogeneity than those components of the internal anatomy of the stem, as can be seen from Table XXVI.

Table XXVI. *Soil variation expressed as a percentage of the total variation for each character.*

Plant character	Soil variation	Total variation	%
Length of straw	1840·864	4342·543	42
Width of lignified tissue	99304·0	318844·0	31
Length of fourth internode	88·642	298·492	29·6
Diameter of fifth internode	2·096	8·941	23·5
Length of fifth internode	105·835	537·182	19·7
Width of sclerenchyma	4218·690	21277·55	19·8
Thickness of sclerenchyma wall	8·346	52·399	15·6
Number of vascular bundles	446·347	4725·7	9·8

The expected percentage for the 16 degrees of freedom for rows and columns is 20 (*i.e.* 16/80), hence the actual percentages obtained for length of fifth internode and width of sclerenchyma are just right, while the calculated percentage for number of vascular bundles is subnormal. However, number of vascular bundles is not consistently associated with degree of resistance to lodging, since the mean number of bundles in Sandy is greater than the mean number in Victory II. Of the characters consistently associated with degree of resistance to lodging, thickness of sclerenchyma wall is apparently one of the most independent of soil variation. Considering this, and the fact that Garber and Olson (22) suggested that thickness of sclerenchyma cell wall might serve as a criterion for the isolation of lodging resistant strains of oats, it seems worth while subjecting the data available for this character to a more critical examination. This will consist in determining if thickness of sclerenchyma wall is independent of other morphological characters, and if not, what is the effect on the mean thickness of wall when the correlated characters are "held constant." A general review of the data reveals that length and diameter of internode appear to show the highest association with thickness of sclerenchyma wall. Hence, the object is to determine the mean values for thickness of sclerenchyma wall when these two variables are "held constant." In other words the mean values arrived at will be of the same order of magnitude as if they had been obtained from the examination of sections which were cut from internodes all of the same length and diameter. The achievement of this result necessitates an analysis of variance and covariance for the characters concerned. The analysis of variance for thickness of sclerenchyma wall has been previously shown in Table XXII. The analyses for the length and diameter of the internode from which the microscopical sections were obtained as well as the covariance analyses will be presented in the following tables.

Table XXVII. *Analysis of variance—length of fifth internode.*

Variation due to	Degrees of freedom	Sums of squares
Rows	8	51·45
Columns	8	68·62
Variety	2	262·12
Spacing	2	24·67
Interaction	4	15·60
Error	56	142·50
Total	80	564·96

The variety means for length of internode are:

Sonas	9·13
Victory II	10·56
Sandy	13·45

Table XXVIII. *Analysis of variance—diameter of fifth internode.*

Variation due to	Degrees of freedom	Sums of squares
Rows	8	1·5823
Columns	8	2·0739
Variety	2	4·5412
Spacing	2	1·9781
Interaction	4	0·2092
Error	56	11·0886
Total	80	21·4733

The variety means for diameter of internode are:

Sonas	5·59
Victory II	5·01
Sandy	5·28

Table XXIX. *Analysis of covariance—thickness of sclerenchyma wall and length of fifth internode.*

Covariation due to	Degrees of freedom	Sums of products
Rows	8	− 7·307
Columns	8	− 5·374
Variety	2	− 76·107
Spacing	2	− 5·992
Interaction	4	0·942
Error	56	− 16·058
Total	80	−109·896

Table XXX. *Analysis of covariance—thickness of sclerenchyma wall and diameter of fifth internode.*

Covariation due to	Degrees of freedom	Sums of products
Rows	8	−0·1956
Columns	8	0·8653
Variety	2	3·5635
Spacing	2	1·9482
Interaction	4	0·0219
Error	56	1·6874
Total	80	7·8907

Table XXXI. *Analysis of covariance—length and diameter of fifth internode.*

Covariation due to	Degrees of freedom	Sums of products
Rows	8	3·249
Columns	8	6·153
Variety	2	−12·387
Spacing	2	− 6·669
Interaction	4	1·515
Error	56	9·940
Total	80	1·801

Let Y = estimated thickness of sclerenchyma cell wall.

y = observed thickness of sclerenchyma cell wall.

$\bar{y}$ = mean thickness of sclerenchyma cell wall.

x_1 = observed length of fifth internode.

$\bar{x}_1$ = mean length of fifth internode.

x_2 = observed diameter of fifth internode.

$\bar{x}_2$ = mean diameter of fifth internode.

Then Y is given by the following partial regression equation:

$$Y = \bar{y} + b\,(x_1 - \bar{x}_1) + c\,(x_2 - \bar{x}_2).$$

The regression coefficients may be found by substituting in the following equations the sums of squares and products due to error from the respective variance and covariance tables and solving for b and c.

The equations are:

$$bS\,(x_1 - \bar{x}_1)^2 + cS\,(x_1 x_2 - \bar{x}_2 x_1) = S\,(yx_1 - y\bar{x}_1),$$

$$bS\,(x_1 x_2 - x_1 \bar{x}_2) + cS\,(x_2 - \bar{x}_2)^2 = S\,(yx_2 - y\bar{x}_2).$$

$$142{\cdot}50b + 9{\cdot}940c = -16{\cdot}058,$$

$$9{\cdot}940b + 11{\cdot}089c = 1{\cdot}687.$$

On solving $c = 0{\cdot}270028$ and $b = -0{\cdot}131523$.

The significance of the regression may be tested by apportioning the sums of squares for "error," shown in Table XXII, into the part due to regression and the part due to deviations from regression. The part due to regression is given by:

$$bS\,(yx_1 - y\bar{x}_1) + cS\,(yx_2 - y\bar{x}_2),$$

$$bS\,(yx_1 - y\bar{x}_1) = -0{\cdot}131523 \times -16{\cdot}058 = 2{\cdot}111996,$$

$$cS\,(yx_2 - y\bar{x}_2) = 0{\cdot}270028 \times 1{\cdot}687 = 0{\cdot}455537.$$

$$2{\cdot}567533.$$

Table XXXII. *Test of significance of regression coefficients.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq.)
Multiple regression	2	2·5675	1·2838	1·2764
Residual	54	16·9297	0·3135	0·5713
Total	56	19·4972		$Z = 0{\cdot}7051$

For corresponding degrees of freedom the 5 per cent. value of Z is less than 0·5994, therefore the regression is significant.

Since the regression is significant, the variability in thickness of sclerenchyma cell walls due to variety, spacing and interaction may be determined, while holding constant the effect of length and diameter of internode on thickness of the wall.

If y, x_1 and x_2 represent deviations from their respective means, then the sums of squares for variation in the thickness of sclerenchyma cell wall, corrected for length and diameter of internode, will be given by $(y-bx_1-cx_2)^2$.

By expansion this becomes

$$y^2+b^2x_1{}^2+c^2x_2{}^2+2bc\,x_1x_2-2b\,yx_1-2c\,yx_2.$$

For convenience the sums of squares and products which enter into the calculation are set out in Table XXXIII.

Table XXXIII.

Variation due to	Degrees of freedom	y^2	$x_1{}^2$	$x_2{}^2$	x_1x_2	yx_1	yx_2
Variety	2	22·0983	262·12	4·5412	−12·387	−76·107	3·5635
Spacing	2	2·0929	24·67	1·9781	− 6·669	− 5·992	1·9482
Interaction	4	0·3647	15·60	0·2092	1·515	0·942	0·0219
Error	56	19·4972	142·50	11·0886	9·940	−16·058	1·6874

The corrected sums of squares for variation in thickness of sclerenchyma cell walls, due to each particular source, may be found directly by multiplying the item in the respective columns by unity, b^2, c^2, $2bc$, $-2b$, $-2c$ and summing the products. The analysis is shown in Table XXXIV.

Table XXXIV. *Analysis of variance for thickness of sclerenchyma cell wall corrected for regression of thickness on length and diameter of internode.*

Variation due to	Degrees of freedom	Sums of squares	Mean square	$\frac{1}{2}\log_e$ (mean sq.)
Variety	2	5·8993	2·9497	1·6922
Spacing	2	0·5092	0·2546	—
Interaction	4	0·0397	0·0099	—
Error	54	16·9297	0·3135	0·5713
				$Z=1{\cdot}1209$

An application of the Z test shows the varietal effect to be highly significant, but this is put forward with the reservation that the test may in this case not be strictly valid. The point is, I understand, under investigation.

The method of correcting the variety means for the regression is shown in Table XXXV, and such significance as there may be is seen to be due to the corrected mean for Sandy being lower than the others.

Considering these results it seems reasonable to infer that even thickness of sclerenchyma cell wall is too unstable a character to be of any use as an absolute criterion of the lodging resistant ability of a variety.

The regression analysis shows that there is a significant negative correlation between length of internode and thickness of sclerenchyma wall. It has been shown in Table XXV that length of internode is easily varied by changes in soil fertility. Consequently, on account of the correlation between length of internode and thickness of wall, it follows that the latter would also be subject to considerable variation. Even in the Latin square experiment under discussion, where soil variation was eliminated as much as possible, the mean values for thickness of sclerenchyma wall were exaggerated by reason of the correlation referred to.

Table XXXV.

	Mean X_1	Mean X_2	Deviation x_1	Deviation x_2	Mean y	bx_1	cx_2	$y-bx_1-cx_2$
Victory II	10·56	5·01	−0·49	−0·28	4·71	0·064	−0·076	4·722
Sonas	9·13	5·59	−1·92	0·30	5·12	0·253	0·061	4·786
Sandy	13·45	5·28	2·40	−0·01	3·87	−0·316	−0·003	4·189
Mean	11·05	5·29						

X_1 = mean length of internode.
X_2 = mean diameter of internode.
y = observed mean thickness of sclerenchyma wall.
$y-bx_1-cx_2$ = corrected mean thickness of sclerenchyma wall.

Thus Sonas, according to the analysis following Table XXII, was considered as having significantly thicker walls than Victory II, whereas the corrected mean values presented in Table XXXV show that there is practically no difference between these varieties.

In the commencement of this discussion the question arose as to whether any of the varietal attributes examined could be taken as an absolute index of resistance to lodging. It can now be definitely said that no one of them could serve such a purpose. The most that could be expected from the characters examined would be their possible value as relative indicators of resistance to lodging. In this capacity their usefulness would depend on the uniformity of the environmental conditions under which the varieties or strains to be compared would be grown. When grown under sufficiently controlled conditions, such easily obtained observations as height, length and diameter of lower internodes would furnish as good evidence of the lodging resistant ability of a variety as any measurements on the internal anatomy. This follows from the correlations existing between parts of the external and internal anatomy of the stem. It is conceivable that the anchorage afforded by the rooting system may form an important part of the lodging resistant potentialities of a variety. Unfortunately no useful observations on the rooting system are available at present. Generally speaking, it can be said that if a number of varieties have equally effective rooting systems from the anchorage viewpoint, their lodging resistant abilities will be closely associated with their relative unresponsiveness to soil fertility. For a certain degree of fertility a relatively unresponsive variety will make slower growth, especially during the early stages, and as a consequence its lower internodes will be shorter than those of a more responsive variety. Without considering the internal structure, short lower internodes, by virtue of the closeness of the nodes, should have a considerable advantage over long internodes. In addition to this aspect it has been shown already that short internodes are accompanied by a stronger internal mechanical tissue than long ones. Thus varietal unresponsiveness to soil fertility has a cumulative effect on strength of straw. In conclusion, it must be admitted that, as yet the results of this investigation cannot offer an alternative to the old established practice of taking type of straw and growth behaviour as a basis for the selection of lodging resistant strains.

SUMMARY.

Three varieties, characterised by the possession of varying degrees of resistance to lodging, were grown in a Latin square with a view to determining if any character could be found which would serve as a stable criterion of resistance to lodging.

Observations were made and analysed for all those morphological characters associated with strength of straw. The characters examined were: tillering, length of straw, lengths of internodes, diameter of fifth internode, thickness of culm wall, number of vascular bundles, width of lignified tissue in a cross-section, and thickness of sclerenchyma cell walls.

The results of the analyses showed that the lodging resistant variety included in the experiment possessed those characters associated with strength of straw to a significantly greater degree than the other varieties. However, all these characters proved to be so subject to the effects of soil variation, that their employment for the isolation of lodging resistant strains could be utilised only on a relative basis.

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GRADING MEAT: THE PRICES GIVEN FOR CARCASES OF DIFFERENT WEIGHTS AND QUALITIES.

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(With Five Text-figures.)

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INTRODUCTION.

THE object of this paper is to define exactly the variations in the price of meat carcases due to variations in weight and to variations in quality, as shown by differences in the conformation according to breed, etc.; that is, to get facts on which a scientific system of grading meat carcases could be based.

While the *per capita* consumption of meat has gone up rather than down during the last decade, the demand is now for small joints two or three times a week rather than one large joint to last the week. This, and the smaller size of families, has led to the demand for smaller joints. With beef there is more scope, in cutting the carcase, to produce joints of smaller size than with mutton or pork, but even with beef, as is shown below, the smaller carcases command the higher price.

Small joints and carcases can be obtained not only by using smaller breeds killed at the same age but also, probably more profitably, by killing the same breed at an earlier age. From figures given below many examples may be seen of the value in price per stone of carcase decreasing with increasing weight to such an extent that the profit obtained would be greatly decreased if the value of the maintenance food during the time taken to attain the increased weight is taken into consideration. With sheep the time of year at which our observations were taken has precluded a consideration of lamb carcases, although with pork and beef a large range of ages is available.

The quality of a carcase depends mainly on the proportions of fat, muscle and bone in the carcase and, as has been shown elsewhere (1), these proportions change as the animal grows up, moreover they change at different rates in different breeds.

As a result of this we find that, although in like breeds the price curves for different weights have much the same course, the price curves for unlike breeds at different weights are not parallel. For example, one breed which commands the highest price for quality (right proportions of muscle, fat and bone) at one weight, may at heavier weights depreciate in value relative to another breed owing to excess deposition of fat. While another breed which at the lighter weights, owing to a high proportion of bone, commands a lower price than the first breed may at the heavier weights, owing to its lack of excess fat, command a higher price than the first breed. That is, for every breed there is a carcase weight, or weights, at which that breed will be at its optimum quality (proportions of muscle, fat and bone); additional evidence on this point will be given in subsequent publications, but this fact should be taken into account when considering the breed differences in the weight-price curves as set out below.

The present paper provides the commercial considerations which are preliminary to a study of the measurements of muscle, fat and bone in the different breeds which have been made on the same material dealt with here, and which will provide an explanation for these price differences.

MATERIAL AND METHODS.

The prices realised at the auction sales of carcases at the Smithfield Show in London for the 10 years 1922–31 inclusive have been analysed statistically. The breed, age and weight of each carcase is recorded, and the carcases are on view before, and at, the time of sale. The cattle and sheep carcases are cut through at the level of the last rib, and the pigs at the shoulder, so that the proportions of muscle and fat can be seen by the buyer. They are purchased by butchers mainly for the London retail trade. Carcases with prizes make more than their commercial value as meat, and so these and all those making fancy prices have been eliminated before analysing the figures. The actual average price coincides fairly well with the average commercial prices in those years, so that the figures can be taken as a fair sample of commercial conditions.

The animals are exhibited in different classes—the cattle and sheep in age classes and the pigs in weight classes. Only the breeds and crosses which have been exhibited in the largest numbers have been averaged out separately, for in many of the breeds and crosses the numbers available were too small to give reliable results.

All prices are given in pence per stone (of 8 lb.), and, since the price level varied in the different years, the carcases were first grouped into weight classes (for sheep by 10 lb. groups 30–39 lb., 40–49 lb., etc.) and averaged; in each year there were generally some carcases which fell into each of these classes so that the price level in different years could be found at constant carcase weights. From results calculated in this way the different years have been grouped, according to the price level existing, into high, medium and low-priced years, so that separate price-weight curves could be drawn for each. When calculating the breed differences in prices no special corrections have been made for the different price levels in different years, since in most cases the distribution of the breeds in the weight classes has been much the same in each year, and only breeds which were regularly exhibited each year were calculated separately. When, however, only two or three animals fall in a weight class (see tables below) the results are liable to error due to this cause, and in such cases therefore the figures derived from them have been placed in brackets in the tables given below.

MUTTON.

The time at which the Show is held (December) limits the range of carcase weights within any one breed, and although there are classes for lambs (born in the same year) and wethers (born in the previous year) no carcases which could be classed as "lamb," except possibly some of the Mountain breeds, were available for study. The number of observations, the range of the carcase weight classes (in 10 lb. groups), and the distribution in the weight classes of some of the principal breeds and crosses are given in Table I.

The average price figures for each weight class for each year, and for all years together, are shown in Table II. Considering all years together, the maximum price (114*d.*) is given for carcases of 40–49 lb., while the price for heavier carcases falls rapidly to 100*d.* at 60–69 lb., 85*d.* at 80–89 lb., 75*d.* at 100–109 lb., and 63*d.* at 120–129 lb.

Table I. *Sheep—number of observations in the different weight classes.*

Carcase weight classes (lb.)...	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100–109	110–119	120–129
Southdown	—	12	39	30	17	7	4	—	—	—
Suffolk	—	—	—	7	16	15	6	3	—	—
Hampshire	—	—	6	11	7	3	4	—	—	—
Cheviot	—	6	16	14	12	8	—	—	—	—
Blackfaced	8	26	13	15	2	—	2	—	—	—
Welsh Mountain	16	12	6	9	5	2	—	—	—	—
Suffolk × Cheviot	—	—	15	9	5	2	—	—	—	—
Southdown × Cheviot	—	3	8	2	3	—	2	—	—	—
Other breeds and crosses	4	23	37	38	36	16	4	4	6	3
All breeds and crosses	28	82	140	135	103	53	22	7	6	3

Table II. *Sheep—average prices* (*in pence per stone of* 8 *lb.*) *for carcases of different weights.*

Figures of doubtful significance, due to small number of observations, are enclosed in brackets.

Carcase weight classes (lb.)...	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100–109	110–119	120–129
Years of high prices:										
1922	—	142	137	135	129	122	109	107	(92)	—
1923	(144)	127	124	117	109	95	—	88	(68)	(64)
1924	(136)	137	128	118	109	100	(76)	88	(74)	(63)
Average (3)	140	135	130	123	116	106	(93)	94	(78)	(63)
Years of moderate prices:										
1925	(104)	101	113	106	96	94	88	—	(68)	—
1926	105	111	118	98	89	84	88	—	—	—
1927	115	110	104	101	89	76	69	—	(64)	—
1928	106	107	96	84	78	71	—	(52)	(68)	—
Average (4)	107	107	108	97	88	81	82	(52)	67	—
Years of low prices:										
1929	103	105	93	86	77	73	71	—	—	—
1930	104	104	98	87	81	75	72	68	—	—
1931	87	99	83	73	72	63	52	50	—	—
Average (3)	98	103	91	82	77	70	65	59	—	—
Average all years	112	114	109	100	93	85	78	75	(72)	(63)
As percentage of price at 40–49 lb.:										
Highest price year	—	100	96	95	91	86	77	75	(65)	—
3 highest price years	104	100	96	91	86	79	(69)	70	(58)	(48)
4 moderate price years	100	100	100	91	82	74	76	(49)	63	—
3 lowest price years	95	100	88	80	75	68	63	57	—	—
Lowest price year	88	100	84	74	73	64	53	51	—	—
All years	98	100	96	88	82	75	68	(66)	(63)	(55)

The Christmas market is well known to prefer heavier carcases than are in demand during the summer months, but, as will be seen in Table II, the drop in price with increasing weight of carcase is large and striking. The slightly lower price (112*d.*) at 30–39 lb. is probably not of real significance, for this group would contain most of the "unfinished" carcases of the smaller breeds, and were the Show held at an earlier date, when well-finished lambs of this weight were available, they would probably have commanded higher prices than the 40–49 lb. class.

In order to show how this weight-price curve varies at different price levels we have compared the different years by showing the price range for each year as a percentage of the price made by the carcases of 40–49 lb. in that year (see Table II and Fig. 1).

Neglecting the 30–39 lb. class which, as explained above, can be considered abnormal, due to the lack of "finish" on the carcases, the curves (Fig. 1) tend to spread out as the higher weights are approached, *i.e.* in times of low prices the buyer differentiates against a heavy carcase more than in times of high prices. For example, if the price of 40–49 lb. carcases in both high and low-priced years is fixed at 100*d.*, then the price of 100–109 lb. carcases in the three lowest-price years is only 57*d.* as compared with 70*d.* for the three highest-price years, a difference of 13*d.*, whereas for the lighter carcases of 50–59 lb. the difference between the high-price and low-price years is less (8*d.*). That is, when

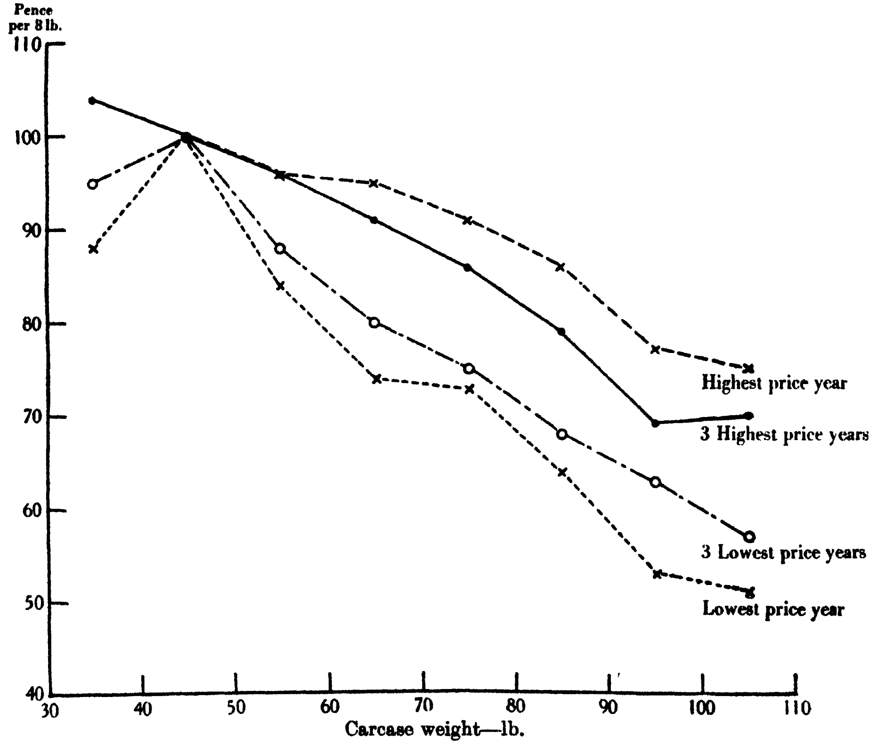

Fig. 1. Proportional prices for mutton carcases of different weights in years of different price levels. Price of 45 lb. carcases made equal to 100 pence in each year.

prices are high the heavy carcase will have a better chance of selling than when prices are low. This is just what was found during the War (with high prices) when the larger breeds of sheep became popular, although, with falling prices since, their popularity has declined. Such are the economic changes which help to cause the popularity of one breed or another.

In order to compare the relative importance of the weight of the carcase in determining the price, as compared with differences in quality at any one weight, the prices obtained for different breeds were averaged separately (see Fig. 2 and Table III). While the maximum range of price due to "weight of carcase" within a breed was from 75*d.* to 120*d.* = 45*d.*, the maximum that could be attributed to quality was (at 75 lb.) from 79*d.* to 105*d.* = 26*d.*, and in most cases it was much less than this. We would suggest therefore that in the grading of mutton carcases the first classification should be on a carcase-weight basis, and that within each weight class there should be subdivision into quality grades. In our opinion this should also be extended to carcase competitions at Shows where classes for different weights (and not for different ages as at present organised) should be specified, so that the judges may be asked to judge for quality only and not to have the more difficult proposition of having to put their preference for certain weights against the variations in quality shown by carcases of different weights. One breed for example will be fitted to win at a certain weight but at a heavier weight it will be too fat, while at this latter weight another breed will have the proportions of muscle to fat fitting it to win. Such a system would sort the breeds out so as to show the weight, or weights, at which each was most suitable for marketing.

Table III. *Sheep—prices (in pence per stone of* 8 *lb.) for carcases of different weights in various breeds.*

Figures of doubtful significance, due to small number of observations, are enclosed in brackets.

Carcase weight classes (lb.)...	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100–109	110–119	120–129
Southdown	—	120	110	98	86	80	75	—	—	—
Suffolk	—		—	106	99	95	91	(94)	—	—
Hampshire	—	—	119	105	97	95	78	—	—	—
Cheviot	—	119	116	109	97	84	—	—	—	—
Blackfaced	105	108	104	107	105	—	(65)	—	—	—
Welsh Mountain	108	105	101	84	79	(90)	—	—	—	—
Suffolk × Cheviot	—	—	112	106	93	(76)	—	—	—	—
Southdown × Cheviot	—	(128)	98	(106)	(89)	—	(54)	—	—	—
Other breeds and crosses	106	119	107	94	89	85	82	68	72	63

From Table I it will be seen that at this time of year (December) the different breeds (approximately 9 and 21 months old) fall into very different weight classes, for example the bulk of the Welsh Mountain carcases fall into the classes 30–49 lb., the Blackfaced into the classes 40–69 lb., the Southdown into the classes 50–69 lb., the Cheviot into the classes 50–79 lb., the Hampshire into the classes 60–79 lb., and the Suffolk into the classes 70–89 lb. These weight-range differences are one of the main causes for the price-range differences between the carcases of different breeds. Thus, while for Suffolk carcases, ranging from 65 to 95 lb., the price-range varies from 106*d.* to 91*d.* (see Fig. 2), the Cheviot carcases range from 119*d.* to 84*d.* but vary in weight from 45 to 85 lb., although when the same weight ranges as for the Suffolk are considered (65–85 lb.) the range in price is reduced to 109*d.* to 84*d.*

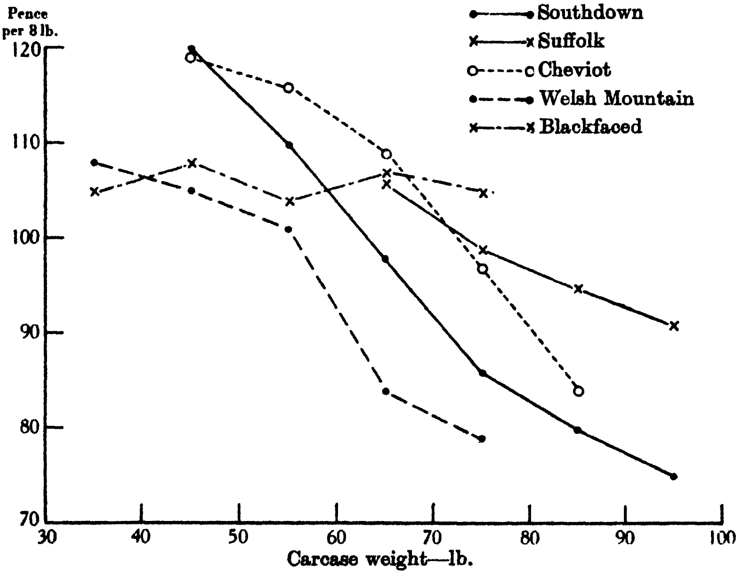

Fig. 2. Prices for carcases of different weights in various breeds of sheep.

From the weight-price curves given in Fig. 2 and Table III it will be noted that the fall in price with increasing weight is not uniform for all breeds; the curves for the different breeds are not parallel but sometimes cross one another.

This is due in our opinion to differences in the quality and "finish" of the carcases of different breeds at the different weights. Evidence from measurements of the fat, muscle and bone in these carcases to support this contention will be given in a later publication. For example, in an early maturing breed like the Southdown it is easy to obtain a high proportion of muscle to bone with a sufficient layer of fat at the light weights so that from 40 to 49 lb. it commands a price of 120*d.*; at this weight, however, the later maturing Blackfaced has not yet attained its full muscular and fat development (although the bone has grown), and so it commands at the same weight only a price of 108*d.* By the time a carcase weight of 70–79 lb. is reached however, the early maturing Southdown has developed too much fat (and, as the butchers say, its carcase has become wasteful), while by this time the Blackfaced has attained the proportions of fat and muscle to bone desired by the public and so the latter (Blackfaced) commands a higher price (105*d.*) than the former (86*d.*).

A study of the results given in Fig. 2 will show that a naturally small breed which is made into a heavy carcase by high feeding will obtain a smaller price per stone than will that of a naturally larger breed of the same carcase weight. For example, the price of the small Welsh Mountain breed carcases after they have obtained a weight of 60 lb. or over fall rapidly in price as compared with those of the larger Blackfaced breed. A similar comparison may be made between the smaller Cheviot and the larger Suffolk breed; at 60–69 lb. the carcase of the Cheviot commands 3*d.* per stone more than that of the Suffolk, but at 80–89 lb. it commands 11*d.* less per stone than the Suffolk. That is, when a small breed is pushed up to heavy weights it puts on too much fat to suit the public taste and the price therefore goes down. Actual measurements of muscle, fat and bone to support this statement will be given in a further publication, but it can be stated here that there appears to be for every breed an optimum carcase weight (or range of weights) at which the fat, muscle and bone are in the right proportions to suit the public taste; below this weight the proportion of bone is too high and above this weight the proportion of fat is too high. How these proportions change as the sheep increases in weight has been shown in a previous publication (1). In connection with the foregoing remarks it should be remembered that the proportions of fat, muscle and bone in the carcase are capable of alteration within certain limits by the plane of nutrition on which it is kept, a low plane of nutrition in an early maturing breed producing the same results as are obtained in a late maturing breed on a higher plane of nutrition (see (2)).

It would thus appear that the fall in price with increasing weight of the carcase is due to two independent factors: (1) the increasing size of the joints, the modern tendency being to favour small joints (see

Wentworth (3)); and (2) the increase in the proportion of fat (beyond the optimum) on carcases of heavy weight for the breed in question.

PORK.

The pigs are shown in two classes for pork pigs, arranged according to live weight from 70 to 100 lb. and from 100 to 160 lb., while a third class for pigs suitable for bacon is open to pigs of 160–220 lb. live weight. In the earlier years of the series (1922, 1923) however, the grouping for pork pigs ranged up to 300 lb. live weight, so that above about 180 lb. carcase weight the results are only reliable within the year concerned.

As these carcases are all purchased for pork purposes, all the classes, both bacon and pork, have been taken together, as they fall into one or other of the weight groups. Weight groups have been taken for carcase weights of 40–49 lb., in 10 lb. intervals, up to 250–259 lb. In some cases pigs heavier than the specified weights were entered, and these were sold at the auction in the same way as the others, although they were ineligible to receive prizes; such carcases have been included in the tables.

The number of observations in the different weight classes and in the different breeds are shown in Table IV. In looking at the distribution of weights in the different breeds, the fact that there are different weight classes at the Show accounts for the different peaks; breed differences however are shown in the general distribution, the larger proportion of the Middle Whites falling below 120 lb. carcase weight, whereas most of the Large Whites lie above 110 lb. carcase weight.

In Table V the average prices for each weight class are given for each year and for all years together. As has been previously pointed out (2, 4), there is a marked drop in price per stone as the weight of the carcase increases. By comparison with Table III for mutton it will be noticed that for similar weights the nature of the drop in price with increasing carcase weight is much the same. It seems probable that the same factors—increased size of joints and increased fatness—are the cause in both. Similarly the difference in the price of light and heavy carcases (see Fig. 3) varies in years of different price levels in the same way as in mutton. These have been calculated on the basis of the 65 lb. carcase group equalling 100 in each year (Table V), and in plotting the curve (Fig. 3) the results have been grouped, because of the small numbers in some groups, in 30 lb. instead of 10 lb. groups so as to give smooth curves. As with mutton, in times of low prices there is a much greater proportional fall in the price of heavy carcases than in the light ones; for example, taking the price of 70 lb. carcases in each price-level group

Table IV. *Pigs—number of observations in the different weight classes.*

Carcase weight classes (lb.)...	40–49	50–59	60–69	70–79	80–89	90–99	100–109	110–119	120–129	130–139	140–149	150–159	160–169	170–179	180–189	190–199	200–209	210–219	220–229	230–239	240–249	250–259
Middle White	5	14	22	14	8	3	14	9	7	5	3	4	4	—	—	—	—	—	—	—	—	—
Berkshire	3	12	18	10	4	4	13	4	8	6	5	2	5	5	4	1	1	1	—	—	—	—
Large White	—	2	11	—	3	4	2	12	2	3	4	8	6	7	—	1	1	2	—	—	—	—
Large White × Middle White	—	5	2	1	1	—	4	1	—	—	—	—	—	—	—	—	—		—	—	—	—
Other breeds and crosses	—	20	12	14	15	6	12	10	8	16	16	12	16	9	2	4	2	1	2	—	2	1
All breeds and crosses	8	53	65	39	31	17	45	36	25	30	28	26	31	21	6	6	4	4	2	—	2	1

Table V. *Pigs—average prices (in pence per stone of* 8 *lb.) for carcases of different weights.*

Figures of doubtful significance, due to small number of observations, are enclosed in brackets.

Carcase weight classes (lb.)...	40–49	50–59	60–69	70–79	80–89	90–99	100–109	110–119	120–129	130–139	140–149	150–159	160–169	170–179	180–189	190–199	200–209	210–219	220–229	230–239	240–249	250–259
Years of high prices:																						
1922	137	137	140	115	126	128	124	—	116	111	103	100	107	100	98	98	—	96	97	—	92	94
1925	—	128	121	118	115	—	112	108	104	105	104	98	92	92	—	94	—	—	—	—	—	—
1926	134	126	134	132	—	122	—	123	114	110	110	82	96	80	96	—	—	—	—	—	—	—
Average (3)	135	130	132	122	120	125	118	116	111	109	106	93	95	91	(97)	(96)	—	(96)	(97)	—	(92)	(94)
Years of moderate prices:																						
1927	104	102	99	98	91	81	77	72	74	68	62	60	60	58	—	—	—	—	—	—	—	—
1928	112	101	100	108	91	84	82	84	77	76	70	—	64	67	—	—	—	—	—	—	—	—
1929	116	115	111	115	113	112	104	98	94	100	104	92	92	92	—	—	—	80	—	—	—	—
1930	—	105	102	103	90	86	77	79	78	72	74	68	72	72	—	—	—	—	—	—	—	—
Average (4)	110	106	103	106	96	91	85	83	81	79	76	73	71	71	—	—	—	(80)	—	—	—	—
Years of low prices:																						
1923	—	89	93	102	88	76	75	76	69	80	62	60	58	50	55	53	53	48	—	—	—	—
1924	—	96	92	92	89	90	86	84	79	73	74	72	71	67	—	72	—	68	—	—	—	—
1931	76	75	91	85	75	69	65	60	54	50	48	47	40	49	—	—	—	—	—	—	—	—
Average (3)	(76)	87	92	93	84	78	75	73	67	68	61	60	56	55	(55)	(62)	(53)	(58)	—	—	—	—
Average for all years:	107	107	108	107	100	97	95	90	86	85	80	75	74	72	—	—	—	—	—	—	—	—
As percentage of the price at 60–69 lb.:																						
3 highest price years	102	98	100	92	91	95	89	88	84	83	80	70	72	69	—	—	—	—	—	—	—	—
4 moderate price years	107	103	100	103	93	88	83	81	79	77	74	71	69	69	—	—	—	—	—	—	—	—
3 lowest price years	83	95	100	101	91	85	82	79	73	74	66	65	61	60	—	—	—	—	—	—	—	—
All years	99	99	100	99	93	90	88	83	80	79	74	69	68	67	—	—	—	—	—	—	—	—

as 100*d.* (see Fig. 3) the difference in price at 90 lb. between high-price years (96*d.*) and low-price years (88*d.*) is small (8*d.*) and increases with increasing weight of carcase, at 150 lb. being 13*d.* (high price 78*d.*; low price 65*d.*). This we would suggest is due to the fact that in times when there is a surplus of pork on the market (times of low prices) the buyer "neglects" the larger carcases and buys the small ones which he can sell best, whereas in times of short supply (times of high prices) he has to bid up for the larger carcases to fill up his requirements for pork.

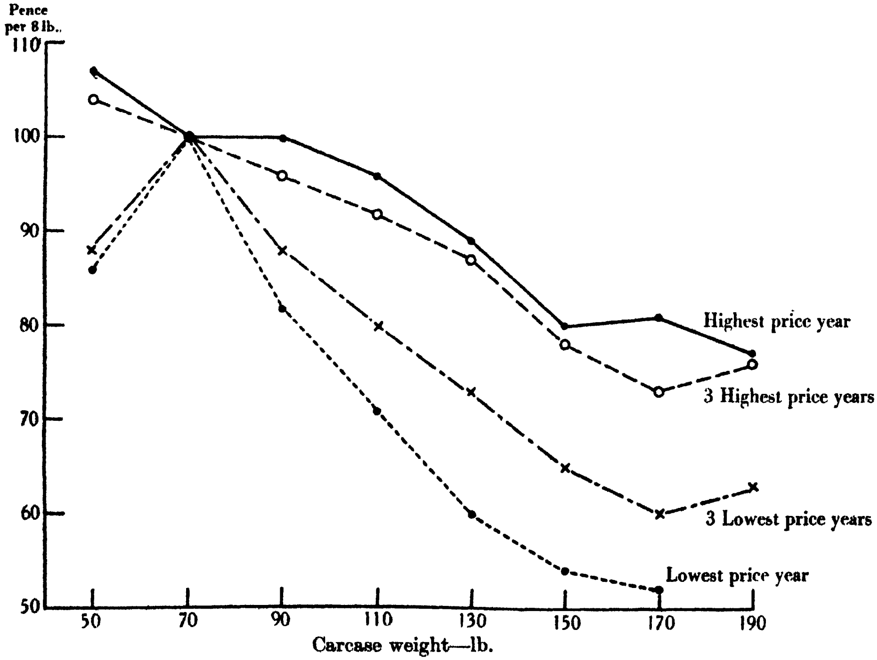

Fig. 3. Proportional prices for pork carcases of different weights in years of different price levels. Price of 70 lb. carcases made to equal 100 pence in each year.

The difference in price due to the "quality" of the carcase, as exemplified by differences in the conformation and proportions of the different breeds (Table VI and Fig. 4), at any one weight shows differences, but, as with mutton, these are less than those due to variations in the weight of the carcase within any one breed. For example in Berkshires there is a drop of 59*d.* (from 109*d.* to 50*d.*) from carcases of 60 lb. to those of 210 lb., while the maximum differences between breeds for carcases of 90 lb. is 18*d.* (Berkshires 99*d.* and Large White 81*d.*). From these figures one sees the necessity for careful attention to the weight classes in the marketing of pork.

Table VI. *Pigs—prices (in pence per stone of* 8 *lb.) for carcases of different weights in various breeds.*

Figures of doubtful significance, due to small number of observations, are enclosed in brackets.

Carcase weight classes (lb.)...	60 (50–79)	90 (80–109)	120 (110–139)	150 (140–169)	180 (170–199)	210 (200–229)
Middle White	99	89	89	75	—	—
Berkshire	109	99	82	70	56	50
Large White	98	81	71	70	64	60
Large White × Middle White	100	(80)	(84)	—	—	—
Other breeds and crosses	104	91	91	79	(85)	(82)

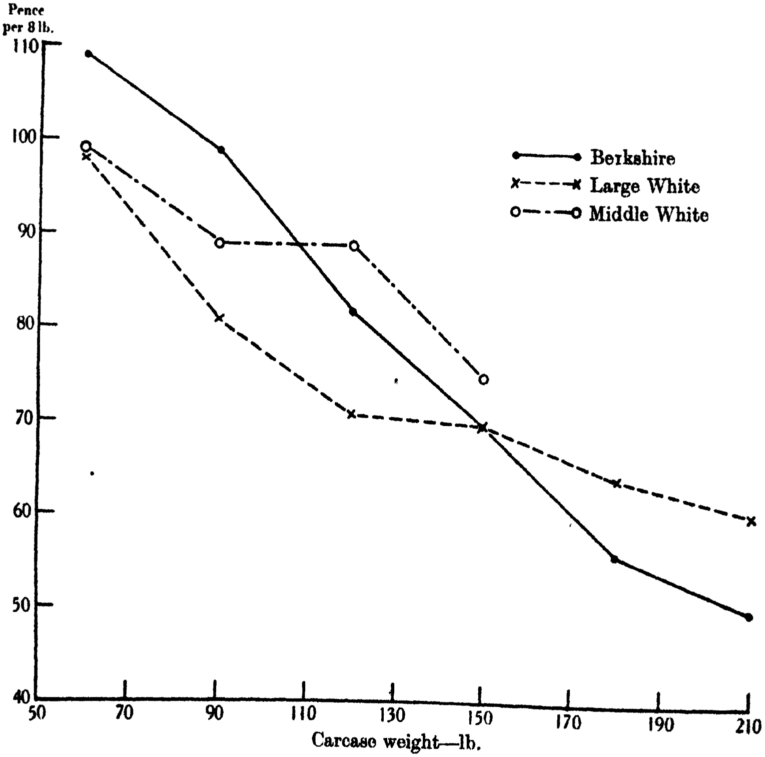

Fig. 4. Prices for carcases of different weights in various breeds of pigs.

As with mutton, the more early maturing breeds command the highest prices at the lighter weights (Fig. 4); in carcases of 60–150 lb. the Berkshire and Middle White command a better price than the Large White, because as has been shown elsewhere (2, 4) they fill out quicker, have better hams, and have a higher proportion of meat to bone. After 100 lb. carcase weight is reached however the early maturing breeds begin to fall off sharply in price, probably owing to the excess fat which is deposited at these weights. Above 150 lb. the relative position of the early and later maturing types is changed, and the later maturing breeds such as the Large White command higher prices than the early maturing ones such as the Berkshire, because in the latter too much fat has developed to make the carcase a saleable one.

BEEF.

The numbers of cattle entered for the carcase classes are small, and when the prize winners have been eliminated there remain but few on which to work. The actual number of observations for each weight class is shown in Table VII.

Table VII. *Cattle—number of observations in the different weight classes.*

Carcase weight classes (lb.)...	300–399	400–499	500–599	600–699	700–799	800–899	900–999	1000–1099
Aberdeen Angus: Steers	3	1	2	3	6	3	—	—
Heifers	1	1	1	2	3	1	1	—
Galloway: Steers	—	—	1	2	1	1	—	—
Heifers	—	—	—	3	1	2	1	—
Red Poll: Steers	—	5	7	1	1	—	—	—
Devon: Steers	2	1	4	1	2	—	1	1
Other breeds and crosses: Steers	3	7	5	6	8	6	6	4
Heifers	—	1	4	6	8	2	3	—
Years of high prices (2)	5	1	5	4	6	3	6	2
Years of moderate prices (4)	2	8	10	10	15	8	6	2
Years of low prices (3)	1	6	9	10	8	4	—	1

Table VIII. *Cattle—average prices (in pence per stone of* 8 *lb.) for carcases of different weights.*

[ ] = figure interpolated.

Carcase weight classes (lb.)...	300–399	400–499	500–599	600–699	700–799	800–899	900–999	1000–1099
Years of high prices (2)	82	88	95	101	97	86	78	74
Years of moderate prices (4)	76	89	94	96	86	75	74	69
Years of low prices (3)	68	88	84	74	70	72	[65]	60
Average all years	75	88	91	90	83	76	72	67
As percentage of price at 500–599 lb.:								
Years of high prices (1922, 1924)	86	93	100	106	102	91	82	78
Years of moderate prices (1925, 1926, 1927, 1930)	81	95	100	102	91	80	79	73
Years of low prices (1928, 1929, 1931)	81	105	100	88	83	86	[77]	71
Average all years	82	97	100	99	91	84	79	74

Although heavy carcases are in better demand at Christmas than at other times of the year, there is a marked decrease in the price of carcases with increasing weight above about 650 lb. For example, on the average of all years (see Table VIII), while carcases of 550 lb. made 91*d.* per stone, carcases of 750 lb. average 83*d.*, those of 850 lb. average 76*d.*, and those of 1050 lb. average only 67*d.* per stone. As with mutton and pork, the lighter class, consisting for the most part of those which have not been finished properly, make less—75*d.* per stone for carcases of 350 lb.

When the years in which high, low, and medium prices rule are considered separately however (see Fig. 5), it will be seen that there are differences in the price-weight curves and particularly in the carcase weight at which the best prices are obtained. So few carcase prices were available in 1923 that this year's results are not included in Table VIII. Since the high-price years are the earlier years of the series and the low-price years the later years, it may be that the differences are due to a change in public taste during this time, or to the fact that in the earlier years of the series the small baby beef carcases were not properly finished, as it was then a new class and the feeders had not much experience in "finishing" these young carcases (under 15 months).

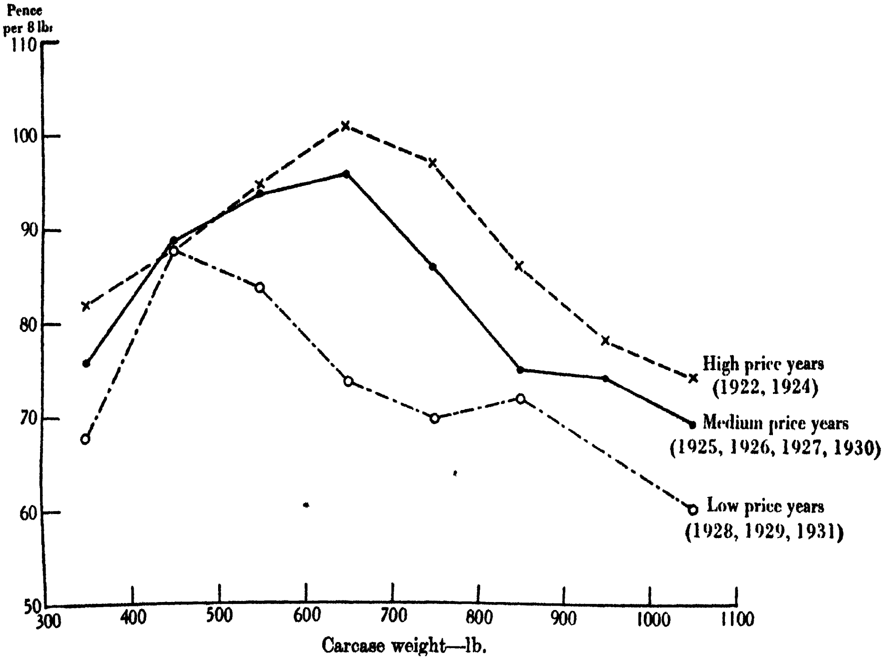

Fig. 5. Prices for beef carcases of different weights in years of different price levels. Actual prices in pence per stone of 8 lb.

Whatever may be the cause, the fact remains that in the latter low-priced years the price falls steadily (except for the unfinished 350 lb. carcases) from 450 lb. (88*d.*) to 750 lb. (70*d.*) and 1050 lb. (60*d.*), just as mutton and pork does. In the earlier years with high prices however the shape of the price-weight curve is different and rises from 82*d.* at 350 lb. to a maximum price (101*d.*) at 650 lb., and then falls steadily to 86*d.* at 850 lb. and 74*d.* at 1050 lb. The shape of the price-weight curve for the medium price years is much the same and rises to a maximum price at 650 lb.

Separate classes are held for steers and for heifers, but as Table IX shows when corresponding weights are considered there is no difference in the price given for heifer beef as compared with steer beef. The numbers for the different breeds (see Table VII) are too small to base definite conclusions on, but there does not seem to be any marked difference in price (see Table IX) due to this cause.

Table IX. *Cattle—prices (in pence per stone of* 8 *lb.) for carcases of different weights in various breeds.*

Carcase weight classes (lb.)...	300-399	400-499	500-599	600-699	700-799	800-899	900-999	1000-1099
Aberdeen Angus: Steers	75	98	83	99	90	85	—	—
Heifers	98	78	96	83	74	56	82	—
Galloway: Steers	—	—	98	67	104	70	—	—
Heifers	—	—	—	84	104	75	82	—
Red Poll: Steers	—	89	88	88	98	—	—	—
Devon: Steers	78	96	93	100	59	—	82	70
Other breeds and crosses. Steers	76	89	90	87	83	75	73	69
Heifers	—	92	96	91	86	82	76	—
All steers	76	97	89	88	85	77	74	69
All heifers	(98)	(85)	96	88	84	74	78	—

GENERAL CONCLUSIONS.

As is shown above there is a greater difference in price due to the weight of the carcase than to the quality as exemplified by breed differences, and it would therefore follow that the first essential in grading meat carcases is to make weight classes and then to subdivide these weight classes into grades according to quality. Why this should be so one can see when one realises that the butcher has week after week to supply households with the same sized joint and so, especially with mutton and pork where the method of cutting is more limited than in beef, his first requirement is carcases of uniform weights.

To increase one's trade in any product one should supply what is in greatest demand, for if this is not forthcoming then the public turn to other products which suit them better. In our opinion the higher price offered for carcases of smaller weights is an indication of public demand for these weights. Although perhaps the actual volume of trade in the medium-weight carcases is now above that of the light-weight carcases, the fact that higher prices are given for the lighter carcases denotes an unfulfilled supply of these as compared with those of medium weights, *i.e.* it points to the direction in which extra trade possibilities exist. This supposition is borne out by the fact that in times of over supply, and consequently low prices, the prices paid for the larger carcases are relatively lower than in times of high prices.

In his analyses of the wholesale prices for beef and mutton at the Metropolitan and London Central Meat Markets, Murray (5) found that, during the period when prices decreased, first-quality cattle decreased 1·48 per cent. whereas inferior cattle decreased 1·63 per cent. in price, and that when prices improved again inferior cattle increased at the rate of 1·10 per cent. and prime cattle at 0·86 per cent. per annum. Although his figures and ours approach the subject from different angles, both show the same relative difference in price between the best and less suited carcases during the years of high as compared with those of low prices, *i.e.* in times of low prices the demand for inferior carcases falls off to a greater extent than that for the best qualities.

Since the weight-price curves for carcases from the different breeds and types of sheep and pigs do not run parallel, owing to the different weights at which the different breeds mature (*i.e.* in proportions of muscle and fat to bone) or over mature (*i.e.* put on too much fat), it would appear better to institute weight classes in carcase competitions at Shows rather than age classifications. Moreover, since with beef there appears to be very little difference in price due to sex, it would seem that sex differences in classes might be eliminated, and in place of these classes might be instituted for animals of different weights. By such an arrangement each breed would find, by trial and error, the range of weights over which that breed best fitted market requirements. This system has already been working satisfactorily with pork and bacon for a number of years and might with advantage be adopted also for mutton and beef.

From the results given here, taken in conjunction with the measurements of fat, muscle, and bone in the carcases (the results of which will be published later), it would appear that within each weight class the quality of the carcase depends on the proportions of these tissues. In the lower weight classes for the breed the prevailing fault is a low proportion of muscle to bone, while in the higher weight classes for the breed in question the prevailing fault is in the high proportion of fat to muscle. Thus it would appear that, from a comparison of breeds, the decrease in price with increase in weight of the carcase is due to two factors: (1) to increase in the size of the joints, and (2) to increase in the proportion of fat with increasing weight of the carcase within the breed.

From the weight-price curves given above it should be possible to calculate, with a fair degree of accuracy, the price of carcases of any other weight when the price at any one weight is known.

Our thanks are due to the Officials and Secretary (Mr Leonard Bull) of the Smithfield Club, and to the Auctioneer, Mr C. E. Coggan, for their interest and help in collecting the records.

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THE VALUE OF COVARIANCE IN ANALYSING FIELD EXPERIMENTAL DATA.

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(With Two Diagrams.)

In recent years attention has been directed to the possible value of the analysis of covariance in interpreting the results of field experiments; this is a logical extension of the method of the analysis of variance introduced by Fisher, and has been described by him (3).

One of the present writers (6) has studied the value of the method in correcting yields of annual crops on the basis of plot yields secured in previous uniformity trials; the conclusion reached was that the practical value was very limited for such crops. On the other hand greater possibilities appear to exist with perennial crops, and workers with tea (2), with cacao (1) and with rubber (5) have produced results indicating substantial reductions of error by this means. With perennial crops, in which the actual plants remain the same throughout, not only is a greater reduction of error obtained than with annual crops, but also there is more justification for the labour of preliminary uniformity trials, because the duration of the experiment is, in general, longer.

The method need not, however, be limited in its application to the use of the results of uniformity trials. With annual crops it is probable that there is greater scope for its use in correcting for uncontrolled and unforeseen differences arising in the early stages of an experiment, and in analysing the development of the crop, step by step. Neither of these aspects has yet received attention, though Immer (4) has studied covariances between harvest observations with sugar beet, *e.g.* number of beet, yield and sugar percentage.

The writers encountered a case where the method was extremely helpful and regard it as a good example of the lines along which the application of the analysis of covariance might be extended. An experiment with four kinds of autumn-sown beans was laid down in which it was required to sow equal numbers of viable seeds on all plots; in spite of all precautions it was found to be impossible to do this on a field scale. When the harvest yields were obtained it was observed that some of the differences between kinds of seed were parallel to differences in seed rate. It was, of course, impossible to determine the actual number of beans sown on each plot, but it was considered that the number of plants established in January, when germination was complete, would give a fair measure of the number of viable seeds sown. The kinds of seed had the same relative placing in yield at harvest as in plants established in January; some further analysis was therefore necessary to ascertain whether yield differences at harvest were due to factors other than difference in plant establishment. The analysis was extended to include other observations with the object of building up as complete a picture as possible of the changes occurring during the development of the crop.

The experiment was carried out in 1932–3 on the University Farm, Cambridge. It consisted of ten blocks, within each of which the four kinds of seed were completely randomised; these kinds were new (N) and old (O) seed of each of two varieties, H and C. The present paper does not give the final decision as to the relative merits either of old and new seed or of the varieties, as work on this problem is still being continued. Each plot was 16 yd. long and eight rows wide; eight pegged sample yards were taken at random from each plot, with the restrictions that one was taken from each row and one from each 2 yd. distance down the plot, the same yards being used for all observations. The statistics of this paper are derived from the 8-yd. totals of the plots.

The observations made are shown in the first column of Table I. Of these the number of viable seed sown could not be obtained for each plot, but was calculated from the total weight of seed sown of each kind and the laboratory germination percentage. The absence of plot figures for this variable renders it useless for statistical treatment; the figures as shown reflect the uncontrollable inequalities which occurred in drilling.

It should be explained that the plant count in December was deliberately made early to determine the relative speeds of germination of the kinds. As mentioned above germination was complete by January, and that count therefore gave the earliest observation on which correction for the uncontrolled inequalities of seeding might be based. Up to that point, also, it may be presumed that developmental factors (to which later observations became increasingly subject) had had a minimum effect. The subsequent observations call for no comment, and columns 2–5 give the means for each kind of seed.

For the analysis of yield, covariance estimates were calculated be-

Table I. *Observed and corrected means.*

Variable	Observed means					Means after correction by the regression on the previous variable					Mean harvest yield after correction by the regression on the variable in column 1				
	HN	HO	CN	CO	S.E. of 1 plot	HN	HO	CN	CO	S.E. of 1 plot	HN	HO	CN	CO	S.E. of 1 plot
Estimated no. of viable beans sown	126·3	132·5	121·0	119·2	—	—	—	—	—	—	—	—	—	—	—
No. of plants in December	71·9	54·3	67·8	52·1	11·40	—	—	—	—	—	1023·2	1006·3	921·1	889·4	168·27
No. of plants in January	99·6	91·8	84·8	78·9	9·70	93·5	96·0	81·1	84·5	7·03	1036·7	967·7	958·3	877·3	173·16
No. of shoots in March	172·6	146·8	152·6	121·5	23·47	154·5	141·8	159·2	138·0	17·32	1001·2	980·3	935·9	922·6	162·95
No. of shoots in April	203·8	169·2	177·2	149·1	24·61	181·6	170·6	173·4	173·7	12·27	967·7	995·3	939·2	937·8	152·94
No. of stems at harvest	122·8	99·1	110·8	88·3	12·38	111·5	101·3	109·9	98·3	7·98	897·7	1035·3	893·9	1013·1	126·40
No. of pods at harvest	695·8	638·4	609·7	521·4	99·89	582·5	678·1	573·9	630·8	61·07	934·4	939·3	958·3	1008·0	45·80
No. of beans at harvest	1964·2	1818·2	1797·6	1613·8	310·72	1721·2	1750·7	1817·9	1904·0	58·46	976·8	965·4	947·8	950·0	35·64
Yield at harvest (gm.)	1066·6	976·1	947·3	850·0	172·02	As in the last 5 columns of the line above					—	—	—	—	-

tween yield on the one hand and each of the other variables on the other, and also between each successive pair of variables. As an example of the procedure, the case of yield and stems at harvest is given in full.

Analysis of variance of yield:

	Degrees of freedom	Sum of squares	Mean square	S.D.	$\log_e$ S.D.	z
Blocks	9	1,011,806	112,423	—	—	—
H *v.* C	1	150,614	150,614	388·09	5·96125	0·81365
N *v.* O	1	88,274	88,274	297·11	5·69411	0·54651
Interaction	1	116	116	—	—	—
Error	27	798,979	29,592	172·02	5·14760	—
Total	39	2,049,789				

For $n_1=1$, $n_2=27$, $P=0{\cdot}05$ when $z=0{\cdot}7187$; $P=0{\cdot}01$ when $z=1{\cdot}0191$.

Thus with uncorrected yield variety H gave a higher yield than variety C, P for that comparison being less than 0·05. New seed gave a higher yield than old seed but the difference was insignificant, and there was no interaction between age of seed and variety.

Taking X to denote the number of stems at harvest and Y to denote yield (x and y being their deviations from their means), the following statistics were calculated:

	Degrees of freedom	Sum of squares (Sx^2)	Sum of squares (Sy^2)	Sum of products (Sxy)	r_{xy} $\left(\frac{Sxy}{\sqrt{Sx^2}\sqrt{Sy^2}}\right)$	$b_{y\,.\,x}$ $\left(\frac{Sxy}{Sx^2}\right)$
Blocks	9	4827·0	1,011,806	37,696	0·539	—
Treatments	3	6639·3	239,004	35,674	0·896	—
Error	27	4139·2	798,979	39,849	0·693	9·6272
Total	39	15605·5	2,049,789	113,219	0·633	

It thus appears that there was, within blocks and treatments, a significant (see below) residual correlation coefficient measuring the causative effect concerned; in order to correct yield for stems at harvest, use was made of the regression coefficient calculated in the same line, and an analysis of the variance of $y-bx$ was drawn up. For this purpose it was unnecessary to calculate the corrected yields of the individual plots, the necessary figures being obtained by applying the equation

$$S\,(y-bx)^2 = Sy^2 - 2bSxy + b^2Sx^2$$

to the sums of squares and products shown above. Deducting one degree of freedom from the error line, the following analysis was obtained:

	Degrees of freedom	Sum of squares ($S\,(y-bx)^2$)	Mean square	S.D.
Blocks	9	733,373	—	—
Treatments	3	167,473	—	—
Error	26	415,343	15,975	126·40
Total	38	1,316,189		

In order to carry out further analysis of the treatment sum of squares, corrected mean yields for each kind of seed were calculated as shown below:

Kind of seed	Mean yield (Y)	Mean no. of stems (X)	($y-bx$)	Mean corrected yield ($\bar{Y}+y-bx$)
HN	1066·6	122·8	−62·4	897·6
HO	976·1	99·1	75·3	1035·3
CN	947·3	110·8	−66·1	893·9
CO	850·0	88·3	53·2	1013·2
General mean	960·0 ($\bar{Y}$)	105·25	—	960·0

The further analysis[1] was:

	Degrees of freedom	Sum of squares ($S(y-bx)^2$)	Mean square	S.D.	$\log_e$ S.D.	z
H *v.* C	1	1,664	1,664	—	—	—
N *v.* O	1	165,122	165,122	406·35	6·00722	1·16773
Interaction	1	846	846	—	—	—
Error	26	415,343	15,975	126·40	4·83949	—

With $n_1=1$, $n_2=26$, $P=0{\cdot}01$ when $z=1{\cdot}0220$.

With uncorrected yields variety H gave a higher yield than variety C, P being less than 0·05, and new seed gave a higher yield than old, the difference being insignificant[2]; it is now seen that when corrected for number of stems, the significance of the H *v.* C comparison is lost (the major part of the difference lying in the number of stems), and old seed becomes significantly superior to new (as having more beans per stem).

The corrected means derived by the above method are shown in the second and third parts of Table I. The significance of the differences, both with observed and with corrected means, and the correlation coefficients calculated are shown in Table II, where the residual correlation coefficients are italicised. In all cases the interaction was insignificant so that the straight comparisons of variety and age of seed are all that is required.

It will be observed that the residual correlation coefficients differ appreciably from the total correlation coefficients, because from them has been removed the effect of heterogeneity of material; they are thus the best estimates of the true relations existing and are therefore the proper figures to use in calculating the regressions. With the relation between yield and the number of plants in January the gross correlation of +0·538 was very largely due to correlations existing between blocks and between treatments, the residual correlation coefficient falling to the insignificant value of +0·156; in other words, the yield at harvest did not depend to any appreciable extent on the number of plants in January. The significance of these correlation coefficients may be tested by taking the degrees of freedom as one less than the corresponding figures shown in the analysis of variance; for $P = 0{\cdot}05$ the values must be, in the order given, as large as 0·632, 0·950, 0·375 and 0·312.

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[1] In this table the total sum of squares for treatment is 167,632 as compared with 167,473 shown previously; the discrepancy is due to the approximation of the mean yields to one decimal place.

[2] The writers have not studied the question of the strict validity of the z test in the analysis of variance of $y-bx$, the point being, they understand, under investigation.

Table II. *Developmental studies and yield. Correlation coefficients and significance of differences with observed and with corrected figures.*

Variable	Significance of differences with observed figures	Correlations* with previous variable	Significance after correction by the regression on the previous variable	Correlations* with yield at harvest	Significance of yield differences after correction by the regression on the variable in column 1
No. of plants in December	H > C, insig. N > O, $P<0{\cdot}01$	—	—	+0·639 +0·742 *+0·280* +0·468	H > C, $P<0{\cdot}05$ N > O, insig.
No. of plants in January	H > C, $P<0{\cdot}01$ N > O, $P<0{\cdot}05$	+0·448 +0·604 *+0·703* +0·582	H > C, $P<0{\cdot}01$ O > N, insig.	+0·686 +0·978 *+0·156* +0·538	H > C, insig. N > O, insig.
No. of shoots in March	H > C, $P<0{\cdot}01$ N > O, $P<0{\cdot}01$	+0·223 +0·897 *+0·690* +0·545	C > H, insig. N > O, $P<0{\cdot}01$	+0·710 +0·969 *+0·368* +0·628	H > C, insig. N > O, insig.
No. of shoots in April	H > C, $P<0{\cdot}01$ N > O, $P<0{\cdot}01$	+0·603 +0·987 *+0·872* +0·794	H > C, insig. N > O, insig.	+0·813 +0·955 *+0·489* +0·682	H > C, insig. O > N, insig.
No. of stems at harvest	H > C, $P<0{\cdot}01$ N > O, $P<0{\cdot}01$	+0·786 +0·982 *+0·775* +0·853	H > C, insig. N > O, $P<0{\cdot}01$	+0·539 +0·896 *+0·693* +0·633	H > C, insig. O > N, $P<0{\cdot}01$
No. of pods at harvest	H > C, $P<0{\cdot}01$ N > O, $P<0{\cdot}05$	+0·718 +0·873 *+0·800* +0·782	H > C, insig. O > N, $P<0{\cdot}01$	+0·922 +0·994 *+0·966* +0·908	C > H, $P<0{\cdot}01$ O > N, insig.
No. of beans at harvest	H > C, insig. N > O, insig.	+0·975 +0·994 *+0·983* +0·965	C > H, $P<0{\cdot}01$ O > N, $P<0{\cdot}01$	+0·968 +0·996 *+0·979* +0·955	H > C, insig. N > O, insig.
Yield at harvest	H > C, $P<0{\cdot}05$ N > O, insig.	As columns 5 and 6 in line above			—

* Correlation coefficients in the order: Blocks,
Treatments,
Residual,
Total.

A study of the errors of the observed and corrected figures in Table I, in conjunction with the residual correlation coefficients in Table II, shows the pronounced effect of a high correlation in the reduction of error of the corrected figures as compared with the observed. Thus the original error for yield was 172·02 and this showed a progressive reduction with increase of correlation; the reduction was inappreciable with the pre-harvest counts, but amounted to as much as 80 per cent. as a result of the correlation of number of beans and yield.

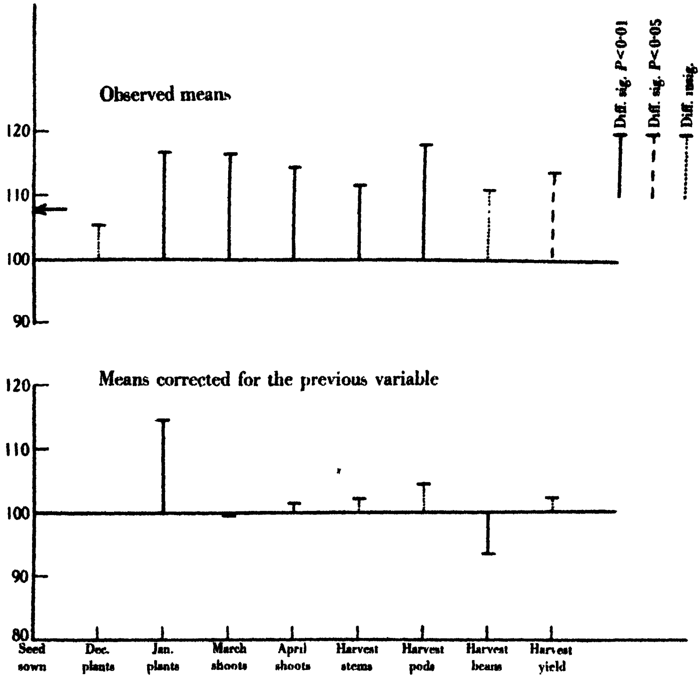

Diagram I. Variety H shown as a percentage of variety C.

Representations of the results are given in Diagrams I and II, the first of which deals with the comparison of the two varieties and the second with comparison of new and old seed. The upper part of Diagram I shows variety H as a percentage of variety C for successive uncorrected observations, and the lower part shows the relation when each is corrected for the previous variable. Diagram II shows new seed as a percentage of old in a similar manner.

Taking the comparison of varieties first, it may be seen that variety H attained to a significant superiority between the December and January counts, and that with minor fluctuations it maintained this position through the succeeding observations up to the number of pods borne. The difference narrowed as regards number of beans, but a slight widening in regard to yield restored the significance. The lower part of Diagram I indicates the changes in the relative position that occurred stage by stage when allowance is made for the position at the beginning of the stage, *i.e.* provides the best estimate of the differerence which would have occurred, had the varieties been equal at the preceding count. Thus it is seen that variety H evinced superiority of germination between December and January: that there were only minor changes from then up to and including pod production, though what changes took place were chiefly in favour of variety H: that that variety produced significantly less beans than would be expected from its pod number (which was responsible for loss of significance at this point in the uncorrected figures): that, finally, the weight per bean was slightly, though insignificantly, greater with variety H.

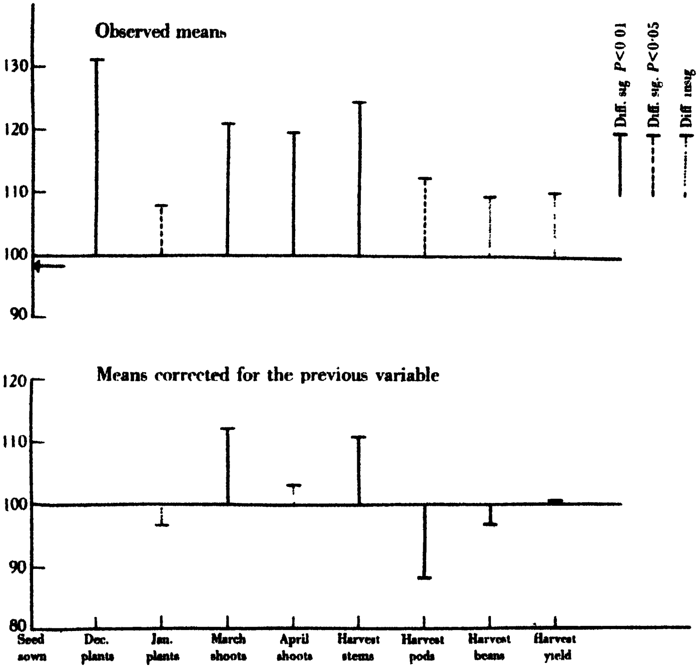

Diagram II. New seed shown as a percentage of old.

Turning to Diagram II, it is very obvious that new seed germinated more quickly than old, a wide difference developing by December; it is clear that the difference was largely due to delayed germination of old seed, the difference having been greatly reduced by January. With number of shoots in March and April and with stems at harvest the differences were large and easily significant. The number of pods produced showed, however, a smaller difference which was less significant, and the differences in number of beans and in yield were still further reduced and did not quite reach the conventional level of significance ($P=0{\cdot}05$). The lower part of the Diagram shows that interesting fluctuations occurred. Whereas the loss of position of new seed from December to January was insignificant, its greater shoot production from January to March was highly significant; from March to April further shoot production was slightly in its favour but the difference was insignificant. Another substantial gain in favour of new seed occurred in the production of harvest stems, when allowance was made for the number of shoots in April. The stems of new seed, however, produced significantly less pods, and each of those pods contained fewer beans; these changes resulted in the destruction of the significance of the difference in the observed figures. The weight per bean was practically the same with both ages of seed.

The original motive for the analysis was to eliminate, if possible, the uncontrolled differences in seed rate by means of the first utilisable observation obtained—the number of plants in January; the elimination had little effect, merely reducing the significance of the differences between the varieties H and C from just above to just below the 5 per cent. point. The low figure of $+0{\cdot}156$ for the correlation coefficient at first appeared surprising, but the substantial influences of later independent developmental factors, sometimes in one direction and sometimes in the other, provide a sufficient explanation.

A more detailed method of analysis might have been adopted. It would have been possible to have regarded the problem as one of multiple correlation, and to have calculated a multiple regression equation to show the effect of the different variables on yield. In order to construct this equation it would have been necessary to calculate not only all the correlation coefficients used in this paper, but also all the intermediate ones; this would have made the work very laborious. Indeed, a full solution of the problem would have required successive multiple regression equations, to determine for each variable the separate effects of all variables preceding it. Such a method might have provided a more complete synthesis of yield, but there seems little likelihood of its giving more information of practical value, than has been obtained by the method of analysis by successive stages adopted here.

SUMMARY.

It is suggested that the covariance method of statistical analysis is of considerable value in correcting for uncontrolled inequalities arising early in an experiment, and in analysing the effects of developmental factors on yield. As an example its application to the results of an experiment with beans is described.

It is with great pleasure that the writers acknowledge their indebtedness to Dr J. Wishart for his helpful criticism throughout the work.

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THE NUTRITIVE VALUE OF LEGUME HUSKS.

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THERE are three by-products obtained from the preparation of legume seeds for human consumption which are marketed as supplemental animal foods, namely, the seed-coats (testa) which are removed from beans, peas and lentils. They are known commercially by various names, "skins," "shells," "husks," "hulls" and as "offals." They are used extensively in the East for the nutrition of cattle, where dehusked legumes enter so largely into the dietary of humans. Bean, pea and lentil husks are all used for stock feeding in Britain, and it was the frequency with which pea husks were found in commercial sheep-feeding mixtures sent for examination, and the knowledge that considerable consignments of bean shells are from time to time imported, that led to this enquiry into their nutritive value. Previous to the adoption of the Foodstuffs and Fertilisers Act, 1926, bean husks were imported into Britain in larger quantities than is at present the case, some of them being ground and added to bean meal, a practice which one has reason to believe has now ceased. Bean husks are seldom fed as such to cattle in Britain, but in France they are given to dairy cows and horses. For cows they are mixed with beet pulp, oil cakes and bran with, it is stated, good results. For horses they are mixed with oats, and an informant, a farmer from Cambrai, mixes them in equal proportions with oats for his working horses, giving to each 30 litres per day. It is claimed that the addition of the husks causes a more complete mastication of the oats and that horses do well on the mixture.

Pea husks, as has been stated, are commonly found in commercial sheep mixtures and they are also bought by sheep farmers who compound their own feeding mixtures; shepherds appear to think highly of the nutritive value of pea husks. Pea husks are also used by dairy farmers in districts where they are available. Lentil husks are usually ground and sold as lentil offal meal, being chiefly disposed of to dairy farmers. These three by-products differ in certain respects. Bean husks as a rule have practically no kernel attached, and consequently their composition is fairly constant. Pea husks contain variable amounts of kernel, there is always some present and occasionally a considerable amount, and it is for this reason probably that their nutritive value is considered to be greater than that of bean husks. The composition of lentil husks is also somewhat variable. The chemical composition of numerous varieties of legume seeds has frequently been determined in regard to their content of protein, fat, N-free extract, fibre and total ash, but comparatively few analyses have been made of the constituents of the ash. McHargue and Roy(1) have made a detailed study of the mineral composition of twelve varieties of American seed and string beans and Klimmer(2) gives the mineral analysis of field beans and peas. There is some confusion in the literature regarding the use of the term "hull," it not being clear in some cases whether the author refers to the seed-coat or to the pod.

A long established custom in nutritional practice based on experience is often found on scientific investigation to be sound, and the question arises as to whether there is justification for attaching any value to these "offals" as food for stock. For the purpose of this enquiry legume seeds have been chosen from a wide range in type. In the case of seven of these the composition of the whole seed, the seed-coat and of the seed freed from the seed-coat have been made separately. Commercial samples of legume husks, which differ from laboratory samples in that they may not be free from portions of kernel, have also been analysed, and the results are given in Table I. From this it will be seen that bean and pea husks are characterised by their low protein and high fibre content. The ash is practically completely soluble in hot hydrochloric acid, it is rich in calcium and poor in phosphorus, whereas, as is well known, the legume embryo contains a high percentage of phosphorus, thus giving to the dehusked seeds, such as are commonly consumed by humans, a preponderance of phosphorus over calcium. The Ca/P ratios of the whole seed (taking China beans of which such large quantities are consumed by cattle in this country as a type), of the husk and of the dehusked seed are respectively: 1:1·32; 1:0·11 and 1:7·29.

NUTRITIVE VALUE OF BEAN, PEA AND LENTIL HUSKS.

In order to determine the nutritive value of the husks, digestibility experiments on sheep were carried out by one of us (S. J. W.) at the I.C.I. Agricultural Research Station, Jealott's Hill.

Table I. *Chemical composition of legume seeds. Dry matter basis.*

	Crude protein	Ether extract	N-free extractives	Crude fibre	Total ash	Silica-free ash	CaO	P_2O_5	Cl	MgO	Na_2O	K_2O
Brazilian beans (*Phaseolus* sp.)	24·67	2·20	64·59	4·03	4·51	4·43	0·35	1·06	0·04	0·36	—	—
Cajanus indicus, Gold Coast	20·45	2·56	65·69	7·14	4·16	4·07	0·29	0·84	0·03	0·28	0·03	1·92
Chick peas, *Cicer arietinum*, Cyprus	20·75	6·67	62·44	6·82	3·32	3·25	0·23	0·58	0·24	0·24	0·06	1·29
Egyptian beans (*Faba* sp.)	29·86	1·68	56·70	8·40	3·36	3·36	0·22	1·22	0·15	0·25	—	—
English field beans, *Faba vulgaris*	26·46	1·98	59·75	8·24	3·57	3·53	0·21	1·29	0·11	0·21	0·19	1·43
"Grey" peas	21·15	1·70	66·35	8·20	2·60	2·60	0·19	0·72	0·10	0·17	0·29	0·86
Lathyrus sativus, India	25·68	1·65	66·43	3·14	3·10	2·54	0·22	0·49	0·19	0·29	0·03	0·91
Lentils, *Ervum lens*, India	25·39	2·03	66·86	3·31	2·41	2·23	0·15	0·70	0·11	0·12	0·01	0·89
Lentils, *Ervum lens*, India	25·78	1·54	67·69	2·44	2·55	2·47	0·15	0·78	0·11	0·10	0·05	1·06
Lentils (imported) "Feeding"	26·75	2·42	57·96	6·38	6·49	3·51	0·28	1·08	0·10	0·31	0·01	1·14
Peas (White Indian)	22·66	2·01	63·85	7·17	4·31	3·20	0·16	0·77	0·12	0·21	0·04	1·34
Peas (Russian)	26·14	2·49	61·61	6·67	3·09	3·09	0·17	0·96	0·09	0·21	0·46	0·86
Phaseolus angularis, India	22·23	1·25	65·78	6·19	4·55	3·56	0·16	0·95	0·01	0·30	0·01	1·48
Phaseolus calcaratus, India	26·10	1·08	64·41	5·10	3·31	3·26	0·17	0·94	0·12	0·28	0·10	1·32
Phaseolus mungo var. *radiatus*, India	26·40	1·58	62·32	5·20	4·50	4·34	0·22	0·92	0·06	0·39	0·07	1·67
Soya beans	38·78	17·65	34·95	3·85	4·77	4·77	0·30	1·11	0·04	0·37	0·08	2·05
Bean husks (commercial)	4·32	0·45	42·30	49·22	3·71	3·67	0·77	0·08	0·25	0·04	0·16	1·19
Bean husks (commercial)	4·38	0·83	43·25	47·93	3·61	3·61	0·73	0·11	0·20	0·09	0·31	0·85
Lentil husks (commercial)	14·70	0·75	51·47	29·68	3·40	2·94	0·45	0·45	0·10	0·13	0·06	0·52
Lentil husks, India	20·25	8·97	47·80	16·88	6·10	5·77	1·34	0·50	0·12	0·40	—	—
Pea husks (commercial)	6·76	0·54	34·75	54·55	3·40	3·39	0·60	0·12	0·14	—	0·10	1·03
Pea husks (commercial)	13·47	0·71	43·42	39·01	3·39	3·32	0·55	0·30	0·11	0·17	0·08	1·06
Pea husks (clean)	4·46	0·21	39·57	52·33	3·43	3·37	0·77	0·09	0·12	0·12	0·07	1·01
Sword beans, *Canavalia ensiformis*, Gold Coast (whole seed)	31·62	3·15	53·97	8·12	3·14	3·14	0·26	0·61	0·08	0·27	0·07	1·25
Sword beans, *Canavalia ensiformis*, Gold Coast (husk)	4·52	1·48	42·14	48·10	3·76	3·62	0·42	0·02	0·05	0·01	—	—
Sword beans, *Canavalia ensiformis*, Gold Coast (kernel)	38·24	3·10	54·50	1·10	3·06	3·03	0·14	0·85	0·04	0·25	0·06	1·23
Algerian beans (*Faba* sp.) (whole seed)	25·66	1·56	59·71	9·64	3·43	3·43	0·25	0·81	0·18	0·26	0·09	1·59
Algerian beans (*Faba* sp.) (husk)	4·16	0·34	42·09	49·59	3·82	2·80	0·77	0·09	0·25	0·08	—	—
Algerian beans (*Faba* sp.) (kernel)	30·36	1·65	62·44	2·27	3·28	3·24	0·10	0·99	0·13	0·22	0·16	1·42
Atta beans (*Pentaclethra macrophylla*), West Africa (whole seed)	24·95	44·38	24·30	3·63	2·74	2·71	0·27	0·61	0·16	0·11	0·06	0·99
Atta beans (*Pentaclethra macrophylla*) West Africa (husk)	7·75	1·62	75·31	9·94	5·38	5·30	1·53	0·09	0·21	0·06	—	—
Atta beans (*Pentaclethra macrophylla*), West Africa (kernel)	24·95	50·86	19·11	2·70	2·38	2·34	0·13	0·50	0·12	0·23	—	—
Bambarra ground nuts, *Vondezia subterrania*, Gold Coast (whole seed)	20·49	6·86	65·07	4·29	3·29	3·27	0·14	0·81	0·06	0·31	0·12	1·49
Bambarra ground nuts, *Vondezia subterrania*, Gold Coast (husk)	6·05	1·28	53·00	37·65	2·02	1·98	0·38	0·31	0·05	0·10	Nil	0·30
Bambarra ground nuts, *Vondezia subterrania*, Gold Coast (kernel)	21·38	7·29	66·53	1·49	3·31	3·26	0·04	0·93	0·06	0·31	—	—
China beans (*Faba* sp.) (whole seed)	26·20	2·06	58·73	9·65	3·36	3·03	0·25	1·21	0·10	—	0·13	1·40
China beans (*Faba* sp.) (husk)	5·36	0·22	41·12	49·70	3·60	3·45	0·65	0·12	0·09	0·08	—	—
China beans (*Faba* sp.) (kernel)	30·86	2·11	62·53	1·22	3·28	3·24	0·09	1·24	0·06	0·23	0·07	1·32
Dolichos lablab, India (whole seed)	26·14	1·47	60·09	8·25	4·05	3·94	0·18	1·06	0·04	0·35	0·08	1·51
Dolichos lablab, India (husk)	8·64	0·56	47·73	39·20	3·87	3·74	0·67	0·25	0·06	0·15	—	—
Dolichos lablab, India (kernel)	38·64	1·22	54·27	1·83	4·04	3·94	0·08	1·45	0·04	0·30	0·07	1·75
Velvet beans, *Mucuna deeringiana*, West Africa (whole seed)	29·10	3·31	55·91	8·35	3·33	3·22	0·18	0·99	0·03	0·30	0·16	1·36
Velvet beans, *Mucuna deeringiana*, West Africa (husk)	1·56	0·67	45·36	49·36	3·05	3·03	0·69	0·11	0·06	0·08	—	—
Velvet beans, *Mucuna deeringiana*, West Africa (kernel)	33·75	3·70	57·71	1·33	3·51	3·49	0·08	1·26	0·06	0·23	0·16	1·50

Composition.

The composition of the husks used in this experiment, together with the figures obtained from other sources, are stated in Table II, expressed in terms of 100 per cent. dry matter.

Table II. *Composition of bean, pea and lentil husks.*
(*Stated as percentages of the dry matter.*)

Source of sample	Crude protein	Ether extract	N-free extractives	Crude fibre	Total ash	CaO	P_2O_5
Bean husks:							
Jealott's Hill (1st experiment)	4·01	0·24	42·16	48·70	4·95	0·74	0·05
,, (2nd ,,)	4·39	0·67	44·95	46·56	3·43	0·65	0·12
Royal (Dick) Vet. College	4·32	0·45	42·30	49·22	3·71	0·77	0·08
,, ,,	4·38	0·83	43·25	47·93	3·61	0·73	0·11
G. S. Robertson(3)	15·60	0·45	27·35	53·60	3·05	—	—
P. de Sornay(4) (*a*)	5·83	0·62	43·70	46·76	3·14	—	—
,, (*b*)	7·16	0·13	44·71	44·73	3·26	—	—
,, (*c*)	3·50	0·78	47·72	45·10	2·90	—	—
Pea husks:							
Jealott's Hill (1st experiment)	6·03	0·38	36·20	54·19	3·24	0·67	0·12
,, (2nd ,,)	4·92	0·38	37·77	53·59	3·34	0·83	0·11
Royal (Dick) Vet. College (*d*)	6·76	0·54	34·75	54·55	3·40	0·60	0·12
,, ,, (*e*)	13·47	0·71	43·42	39·01	3·39	0·55	0·30
,, ,, (*f*)	4·46	0·21	39·57	52·33	3·43	0·77	0·09
Smetham and Dodd(5) (*g*)	5·98	0·83	35·38	54·60	3·25	—	—
,, ,, (*h*)	7·24	0·55	38·42	50·69	3·12	—	—
Kellner(6)	8·30	1·36	36·25	50·81	3·30	—	—
Henry and Morrison(7)	7·44	1·29	40·41	46·98	3·88	—	—
Dept. of Agriculture, Canada(8)	5·96	0·47	36·70	54·32	2·60	—	—
P. de Sornay	7·52	1·37	33·03	55·25	2·85	—	—
Lentil husks:							
Jealott's Hill	12·56	0·81	53·99	29·08	3·56	0·83	0·47
Royal (Dick) Vet. College (*i*)	14·70	0·75	51·47	29·68	3·40	0·45	0·45
,, ,, (*j*)	20·25	8·97	47·80	16·88	6·10	1·34	0·50
Silcock and Sons (*k*)	23·10	1·10	57·20	11·00	6·60	0·66	0·55
	20·15	0·82	54·36	19·23	5·77	—	—
	21·30	1·77	55·75	17·33	3·86	—	—
	22·23	1·98	51·54	13·20	11·44	—	—
P. de Sornay	11·63	0·56	54·32	30·68	2·79	—	—

(*a*) From Mauritius.
(*b*) From Tunis.
(*c*) From Egypt.
(*d*) Commercial husks.
(*e*) Commercial husks containing a higher percentage of pea.
(*f*) Husks removed in laboratory from white Calcutta peas, and free from kernel.
(*g*) White pea husks.
(*h*) Calcutta white pea husks.
(*i*) Commercial sample.
(*j*) Indian sample.
(*k*) Kindly supplied by Messrs Silcock and Sons, Ltd., Liverpool.

It will be noted that there is a close similarity between the first four samples of bean husks, all being commercial samples of imported husk.

The values quoted by de Sornay agree in the main with our values. Robertson's husk is evidently a sample containing a certain amount of bean meal, the beans not being so cleanly decorticated as the average commercial sample.

The figures for pea husk show, on the average, a higher crude protein and crude fibre content than do bean husks, the N-free extractives, however, being somewhat lower. One sample which contained a higher percentage of pea shows a high crude protein content and low fibre content.

Lentil husks obviously differ from bean and pea husks in their relatively high protein content, generally a somewhat higher percentage of fat and a very much lower fibre content. They also contain less calcium and more phosphate. In one sample that was analysed which was sent to the laboratory from India there was an unusually high content of fat; repeated estimations from different portions of the sample showed that the fat was evenly distributed; its source is unknown.

Lentil husks are somewhat variable in their composition, as is seen in the table, where one sample is shown to have 11·4 of ash. Imported lentils designated "feeding lentils" are often exceedingly dirty and frequently contain a very high percentage of weed seeds.

The Indian sample examined together with those kindly supplied by Messrs Silcock and Sons, Ltd., of Liverpool, are outstanding in so far as the crude protein content is concerned, and are in a different category from the other samples of lentil husks.

Digestibility.

It was found that the sheep would not eat the husks alone, and they were, therefore, given a mixed ration of hay and husks. The digestibility of the hay was determined in a prior experiment, using the same sheep, the results obtained being used in calculating the digestibility of the husks.

In the first experiment with bean and pea husks the hay used was of poor quality, and as very low values were obtained for the digestibility of the crude protein, the experiments were repeated using a better quality hay, which supplied more protein in the ration. Lentil husks were also tested in the second series of experiments.

The digestibility coefficients obtained for the legume husks are given in Table III.

The values for ether extract seem high, but are the least accurate since there is such a small quantity of ether extract present that it is difficult to measure the digestibility coefficient with any great degree of accuracy. The important point is the high digestibility of the fibre in the case of all three legume husks, though that of lentil husks is not of such a high order as the other two.

Table III. *Percentage digestibility of bean, pea and lentil husks.*

	Bean husks		Pea husks			Lentil husks
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Kellner	
Dry matter	67·7	67·0	90·2	82·0	—	60·5
Organic matter	68·3	67·8	89·1	83·9	89·0	60·8
Crude protein	—	—	18·1	12·1	71·0	11·9
Ether extract	100·0	100·0	100·0	71·7	73·0	95·5
N-free extractives	57·5	71·9	81·6	82·6	90·0	70·1
Fibre	89·2	80·3	99·8	92·4	94·0	67·3

There is a close agreement between the values quoted by Kellner and the two digestibility trials on pea husks, with the exception of the crude protein.

A low value for this constituent was also recorded with lentil husks, and in the case of the bean husks it was totally indigestible. The digestibility coefficient for lentil husks could not in fairness be applied to the analytical values obtained on the samples supplied by Messrs Silcock, since these had a much higher protein content, indicating the presence of considerable amounts of lentil meal.

The digestibility of the crude protein of the lentil husks and of the bean and pea husks used in the second series of experiments was also determined, *in vitro*, by Wedemeyer's modification of Stutzer's pepsin-hydrochloric acid method. In the case of bean husks anomalous results were obtained, and the amount of insoluble nitrogen was greater than that originally present in the husk. It is thought that this might be due to inactivation of the pepsin by some substance in the beans which resulted in the precipitation, in an insoluble form, of some of the nitrogen of the pepsin. In the normal course of events the whole of the nitrogen supplied in the added pepsin is itself soluble. This question is being investigated further.

The value for the digestibility of the crude protein of the pea husks, by this method, was 63·2 per cent., which is more in line with the value obtained by Kellner. Correcting the faecal nitrogen of the sheep (on pea husks) for metabolic nitrogen, by subtracting any pepsin-soluble nitrogen in the faeces, gave a value of 79·4 per cent. for the digestibility of pea husks.

In the case of bean husks this procedure also gave anomalous results.

It should be remembered that the values obtained by animal metabolism experiments are apparent digestibility coefficients, and do not take into account that portion of the faecal nitrogen which is of metabolic origin. They are, however, the figures which most nearly approximate to the value of the foodstuff to the animal. The value for the digestibility of the crude protein of the lentil husks, determined *in vitro*, was 15·82 per cent., which is not much higher than that obtained by the animal experiment.

Nutritive value.

From the results of the animal experiments the following starch equivalent and digestible crude protein values have been calculated:

Table IV. *Nutritive value of bean, pea and lentil husks.*

	Starch equivalent	Digestible crude protein
Bean husks (1st experiment)	55·1	0·0
„ (2nd „)	57·6	0·0
Pea husks (1st „)	68·9	1·1
„ (2nd „)	65·9	0·6
„ (Kellner)	64·1	5·1
Lentil husks	53·1	1·5

It will be seen that both bean and pea husks had a fairly high starch equivalent, notwithstanding their high fibre content. The value for lentil husks is of the same order as that of bean husks, but some digestible crude protein is available in the case of the former.

The starch equivalent assigned to pea husks in these experiments is similar to that given by Kellner, whose correction for fibre has been used in the calculation of the values. As a source of protein, bean and pea husks must be considered of no value. Notwithstanding this, they are commonly regarded as useful supplemental foods for sheep. Many food merchants who utilise them in their sheep mixtures consider that their value lies in the fact that they add "bulk" to a concentrated ration. In Table V three concentrated rations are considered, which are commonly used for ewes before, during and after lambing. It will be seen that in the first two the Ca/P ratio is definitely unbalanced, if we assume a Ca/P ratio of 1:1 to be approximately the optimum. On the other hand, in the case of ration No. 3 consisting of linseed cake, peas and pea husks, a ration which is rather popular among shepherds in some districts, the ratio of Ca:P is 1:1·24 which, particularly where the supply of minerals may fall below that actually required—as it may well do at lambing time—is preferable to that of either ration 1 or 2. While therefore pea husks contain a negligible quantity of protein it may well be that their inclusion in a diet, particularly at lambing time, may have a definite beneficial effect, especially when mineral mixtures are not supplied. Pea husks were favoured by shepherds before the attention of science was directed to the mineral needs of sheep, and consequently before artificial food mixtures were fortified with minerals as is so commonly the case to-day. There would therefore appear to be some justification for including a certain proportion of pea husks in the mixture of concentrates given to sheep, provided that the protein content of the mixture is not reduced thereby.

Table V. *The composition of three concentrated daily rations commonly fed to ewes at lambing time**.

	Food (oz.)		Dig. protein (gm.)	Starch equivalent	CaO (gm.)	P_2O_5 (gm.)
(1)	Linseed cake	4	27·2	0·18	0·567	2·042
	Bruised oats	4	9·1	0·15	0·170	1·474
	Bran	4	13·6	0·11	0·227	2·948
		12	49·9	0·44	0·964	6·464
					Ca : P = 1 : 3·77	
(2)	Linseed cake	4	27·2	0·18	0·567	2·042
	Oats	4	9·1	0·15	0·170	1·474
	Dried grains	4	13·6	0·13	0·454	1·701
		12	49·9	0·46	1·191	5·217
					Ca : P = 1 : 2·49	
(3)	Linseed cake	4	27·2	0·18	0·567	2·042
	Peas	4	22·7	0·18	0·159	0·794
	Pea husks	4	Nil	0·17	0·612	0·125
		12	49·9	0·53	1·338	2·961
					Ca : P = 1 : 1·24	

* *Animal Nutrition* (1927), R. G. Linton.

Lentil husks are commonly used for the feeding of dairy cows, but the samples fed will normally be of the high protein class, with an admixture of the kernel, and will doubtless show a higher digestibility of the crude protein than is the case when the true husk is considered.

We wish to take this opportunity of expressing our thanks to the Director, Imperial Institute, London, for kindly supplying much of the material with which this work was done. We have also to thank Mr E. A. Horton who had care of the sheep and the analytical work connected with the digestibility trials.

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THE EFFECT OF SODIUM NITRATE ON THE GROWTH AND NITROGEN CONTENT OF A LUCERNE AND GRASS MIXTURE.

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(With Twelve Text-figures.)

I. INTRODUCTION.

THE influence of mineral nitrogenous manuring upon an association of leguminous and other plants is of considerable agricultural importance. The problem bears on the manuring of grass land, forage mixtures, temporary leys, and of such legumes as clover and lucerne where these are sown in a cereal cover crop. The practice of applying a small dressing of mineral nitrogen to a leguminous crop grown by itself is often held to be beneficial, on the ground that it gives the legume a good start. Thus, in a rotation experiment carried out at Rothamsted, sulphate of ammonia increased the yield of pure clover to an appreciable extent (see *Rothamsted Experimental Station Report for* 1930, pp. 37, 38). Too often, however, a legume, though sown by itself, actually grows in association with a flora of weeds, so that here, too, nitrogenous manuring may be acting upon a mixed flora. Where a legume is being grown, intentionally or otherwise, in association with a non-legume, the response of the crop is complicated by the introduction of the factor of competition.

Numerous field experiments with permanent grass, temporary leys, and forage mixtures, have shown that nitrogen dressings may stimulate the non-leguminous plants to such a degree that they will check the growth of the legumes. In consequence of their effect in diminishing the percentage of legumes, nitrogenous manures often fail to increase the content of protein of the crop. A good example of this was afforded by a forage mixture experiment (oats or barley, with vetches or peas) on arable land, commenced at Rothamsted in 1930. In its first year this experiment gave the results tabulated below (see *Rothamsted Reports for* 1930, 1931, *and* 1932):

Nitrogen added (cwt. per acre)	0	0·2	0·4
Yields of dry matter (cwt. per acre)	25·3	31·8	35·8
Percentage of protein in crop	11·7	9·6	8·6
Nitrogen in the crop (cwt. per acre)	0·42	0·44	0·44

The effect of mineral nitrogen on mixtures of legumes and non-legumes has been very little studied under the better-controlled conditions of pot experiments. Remy and Vasters (3), however, made a complicated pot experiment containing non-legumes with two legumes, and applied nitrogen at four different levels, all of them high. The relation of nitrogen applied to that recovered in the crop is shown in Fig. 1. Only the highest nitrogen dose increased the nitrogen content of the crop; with the other dressings the better growth of non-legumes was offset by decreases in the legumes.

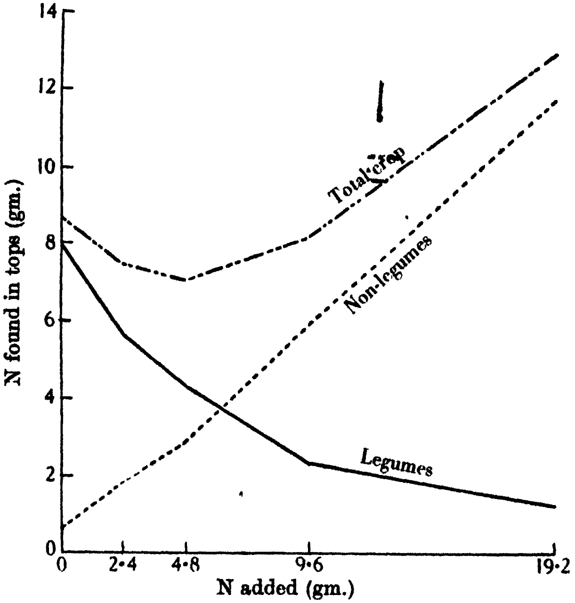

Fig. 1. From data of Remy and Vasters (3).

Evidence from such work, however, does not enable us to distinguish, in the legume, the effects of increased competition from those due to possible directly repressive action of the applied nitrogen. In order, firstly, to estimate the relative importance of these two effects, and, secondly, to determine whether the non-legume sets up competition above or below ground, a pot experiment was carried out during the summer of 1931. In this experiment lucerne was grown alone and with grass, in sand to which three different dressings of sodium nitrate were applied.

II. PLAN OF THE EXPERIMENT.

The experiment was performed in glazed earthenware pots, each containing about 20 kg. of sand having an initial water content of 2 per cent. 10 gm. of precipitated chalk was well mixed with the sand before filling the pots, and to each pot was given 500 ml. of the following plant nutrient solution, made with the usual hydrated salts:

0·5 gm.	K_2HPO_4	0·5 gm.	$NaCl$
0·5 ,,	KH_2PO_4	0·5 ,,	$CaSO_4$
0·5 ,,	$MgSO_4$	0·04 ,,	$FeCl_3$

The pots were divided into the following series each containing twelve parallel pots:

Series	Nitrate manuring	Sowing
A	+0·33 gm. $NaNO_3$	Lucerne alone
B	+1·0 ,, ,,	
C	+3·0 ,, ,,	
AA	+0·33 ,, ,,	Lucerne and Italian rye grass
BB	+1·0 ,, ,,	
CC	+3·0 ,, ,,	

All the nitrate was added in one dose in solution before sowing. The pots were sown on April 25 with 200 lucerne seeds per pot and series AA, BB and CC with 240 seeds of Italian rye grass as well. The lucerne seed was inoculated with an efficient strain of the lucerne nodule bacteria using the technique described by Thornton (4). The pots were arranged in the greenhouse in twelve blocks within each of which the treatments were randomised. They were weighed at the commencement of the experiment and watered with rain water as required to bring them to their initial weight. The plants were thinned out on May 13–15, leaving twenty lucerne plants and, in series AA, BB and CC, twenty grass plants per pot.

III. EARLY GROWTH.

A count of seedlings made on May 5 showed that the higher nitrate dressings significantly delayed germination and early growth of both the lucerne and the grass. The effect on the lucerne was still shown by a leaf count made on May 19. A second leaf count made on May 30 showed that by this date the number of leaves on plants receiving 1·0 gm. of sodium nitrate was no longer significantly lower than on those receiving 0·33 gm. The effect of grass competition was not yet apparent. During June, however, the grass began to show marked differences both in height and number of shoots in the three series. In the AA series it was very weak and etiolated. In series BB and CC it was green, and in CC the growth was much the strongest. The differences were apparent up to the end of the experiment. By June 30 the growth of the lucerne was depressed by the presence of grass but was not significantly affected by the nitrate dressing (Table I). The directly harmful effects of the higher nitrate dressings upon the lucerne, noted in the early growth, were thus no longer detectable by this date.

Table I. *Early growth of the lucerne grown with and without grass.*

Series	Treatment	Mean number of lucerne eaves per pot, May 19	ean number of lucerne ves per plant, May 30	Mean height of lucerne plant June 30
A	+ 0·33 gm. $NaNO_3$	42·0 ± 1·2	3·5 ± 0·08	43 cm. ± 2·4
B	+ 1·0 ,, ,,	39·9 ± 1·38	3·5 ± 0·12	44 ,, ± 2·2
C	+ 3·0 ,, ,,	35·7 ± 1·60	2·8 ± 0·13	39 ,, ± 2·7
AA	+ 0·33 ,, ,,	42·5 ± 1·33	3·4 ± 0·11	34 ,, ± 1·7
BB	+ 1·0 ,, ,,	39·2 ± 1·18	3·2 ± 0·11	30 ,, ± 1·2
CC	+ 3·0 ,, ,,	31·7 ± 1·39	2·8 ± 0·08	31 ,, ± 1·5

IV. REAPING OF THE CROP.

Reapings were made on June 25, July 27, August 28 and October 1, three pots in each series being reaped on each date. The reaping was carried out as follows. The pots to be reaped were left unwatered for several days till the sand became dry. The whole contents were then turned out and the plants lifted out of the sand and gently shaken. It was found possible by this means to separate the roots of the grass and of the lucerne. The sand was then passed through a sieve to catch such fragments of fine grass roots as were left in it. All roots were then washed free from sand and the nodules on the lucerne roots were counted. Tops and roots of both lucerne and grass were separated, weighed in an air-dry condition, and analysed for nitrogen by the Kjeldahl method. The nitrogen estimations were performed by the Chemistry Department of this Station.

Each point shown in the graphs which follow represents the mean of values obtained from three parallel pots.

V. EFFECT OF NITRATE DRESSINGS ON LUCERNE GROWN ALONE.

In series A, B and C, where lucerne was grown alone, the variation in dose of nitrate produced no significant effect upon the yield or the nitrogen content of the tops (Fig. 2). The highest dressing significantly reduced the root growth in the last three months (Fig. 3).

The number of nodules developed by the time of the first reaping in

June was considerably reduced by the highest nitrate dose, but by July the nodule numbers in the three series were not significantly different (Fig. 4). In August and especially in September there was an actual increase in nodule numbers with quantity of nitrate supplied. This result in the last two reapings differs from the usual finding that nodule numbers are reduced by nitrate. In the present experiment rather small nitrate applications were made in April, so that by August the nitrate concentration in all three series may well have been so greatly reduced as no longer to check infection by the nodule bacteria. It does not seem profitable to discuss the reason for the actual increase in nodule numbers with nitrate, since the data do not enable us to test the possible causes that suggest themselves. The greater number of nodules in series B and C was not accompanied by any increase in nitrogen content of the plants, so that less nitrogen must have been fixed per nodule with the higher nitrate applications.

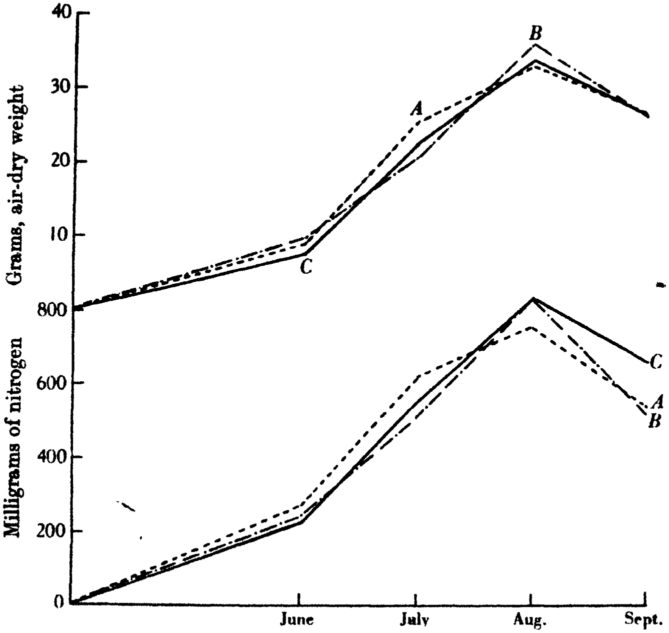

Fig. 2. Lucerne grown alone. Yields and nitrogen content of tops.

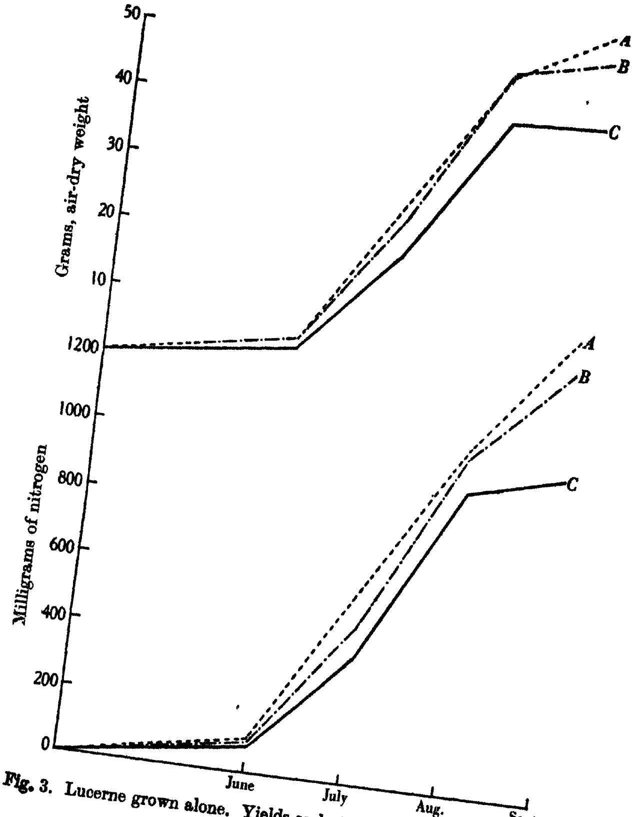

Fig. 3. Lucerne grown alone. Yields and nitrogen content of roots.

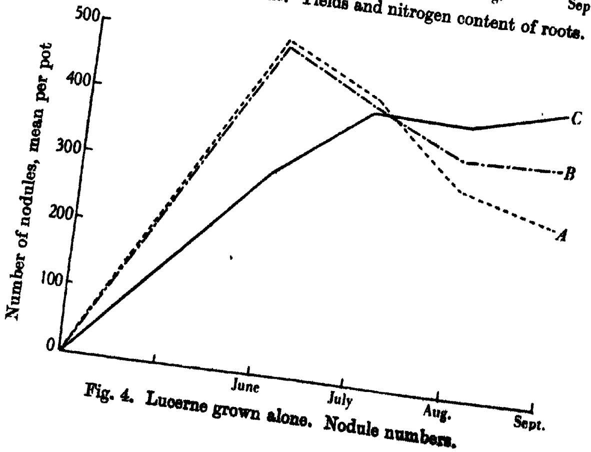

Fig. 4. Lucerne grown alone. Nodule numbers.

VI. EFFECT OF NITRATE DRESSINGS UPON THE LUCERNE-RYE GRASS ASSOCIATION.

In series AA, BB and CC, the growth and nitrogen content of lucerne, grown in association with grass, were inversely related to the dose of nitrate supplied (Figs. 5 and 6). Series CC, receiving 3 gm. of $NaNO_3$, gave a yield and nitrogen content both of lucerne tops and roots that was significantly lower than the other two series from July onwards. Series BB, receiving 1 gm. of nitrate, gave a significantly lower yield and nitrogen content of lucerne tops and roots than series AA in August and September. The nodule numbers in July, August and September, like the root weights, showed a significant inverse relation to amounts of nitrate added (Fig. 7).

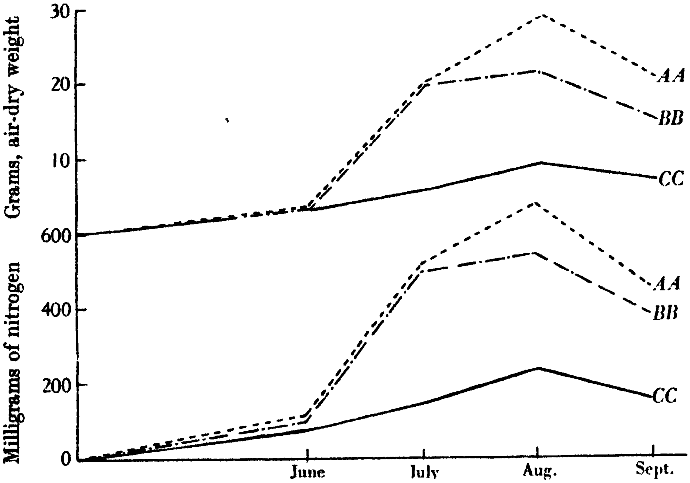

Fig. 5. Lucerne grown with grass. Yields and nitrogen content of lucerne tops.

Growth of the grass was markedly increased by the two larger nitrate dressings (Fig. 8). It seems clear that the harmful effect of these dressings upon lucerne growing with the grass was due to competition. The lucerne grew so much taller than the grass even in series CC, that it can scarcely have been weakened appreciably by shading. It seems probable, therefore, that the lucerne was affected by root competition. This probability is supported by the fact that the total lucerne dry matter in July, August and September was a linear decreasing function of the grass root weights, so that for every gram increase in grass roots the lucerne decreased by

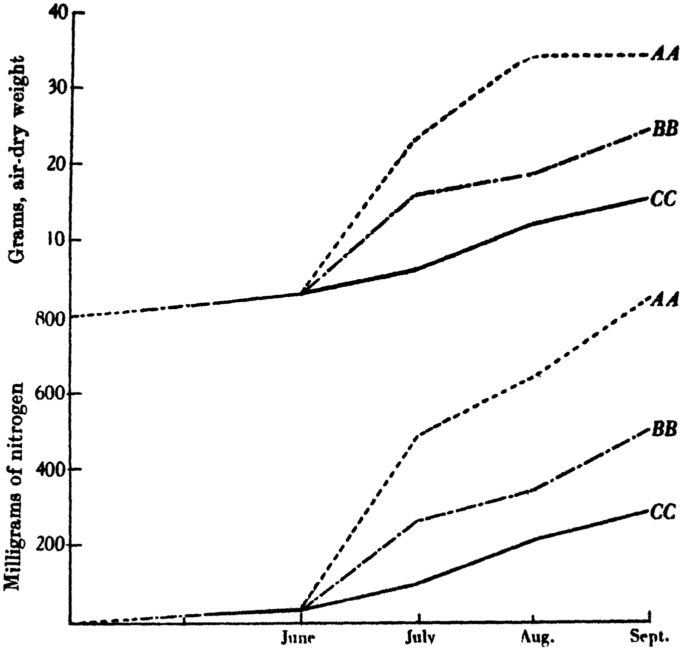

Fig. 6. Lucerne grown with grass. Yields and nitrogen content of lucerne roots.

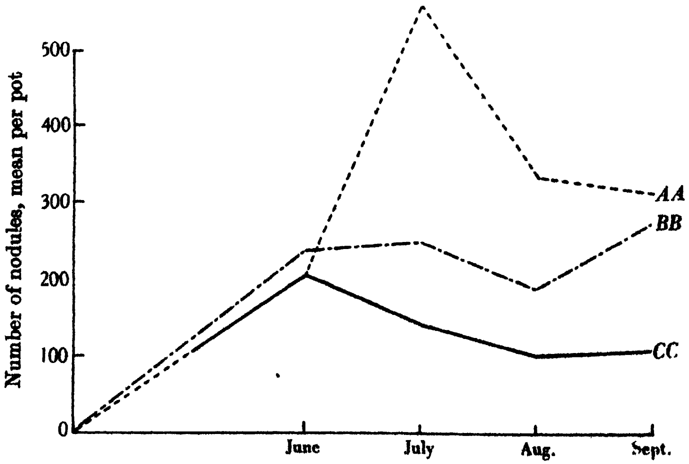

Fig. 7. Lucerne grown with grass. Nodule numbers.

about 0·8 gm. On the other hand the lucerne dry matter was less clearly related to that of the grass tops (Fig. 9).

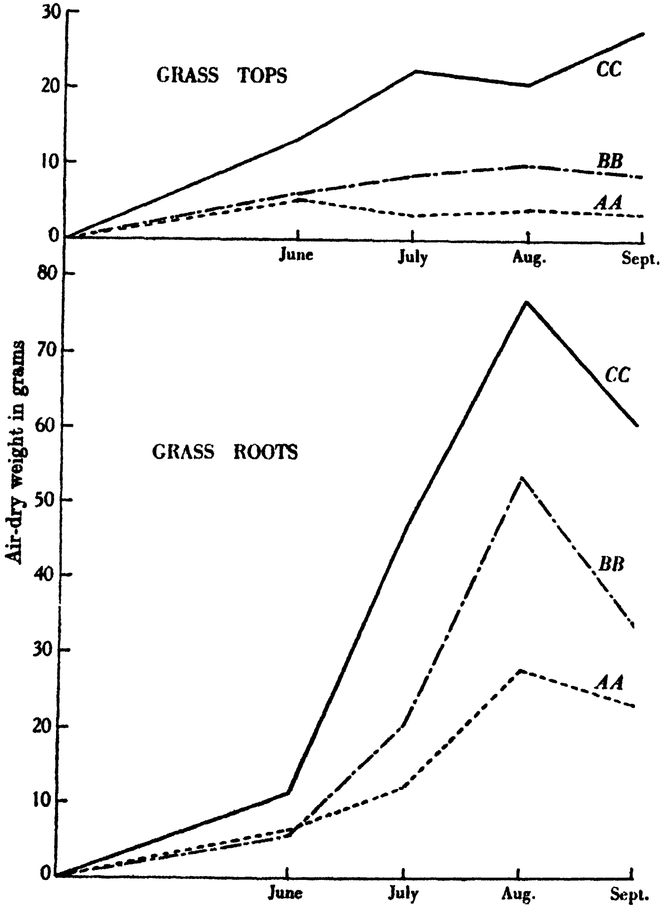

Fig. 8. Yields of grass growing with lucerne.

VII. ABSORPTION BY THE GRASS OF NITROGEN FIXED BY THE LUCERNE.

In series AA and BB, the quantities of nitrogen contained in the grass towards the end of the experiment greatly exceeded the doses of nitrate nitrogen added (Fig. 10). In series AA, where 55 mg. of nitrate nitrogen were added to each pot, the grass was found to contain 132 mg. of nitrogen per pot in July and 300 mg. in August. In series BB, where 163 mg. of nitrate nitrogen were supplied, the grass contained 188 mg. of

N in July and 389 mg. in August. Thus, even if the whole of the nitrate nitrogen had been taken up by the grass and none by the lucerne, considerable additional quantities of nitrogen were gained by the grass. The bulk of this extra nitrogen must have been derived from nitrogen fixed by the lucerne. The fact that grass can obtain nitrogen from lucerne

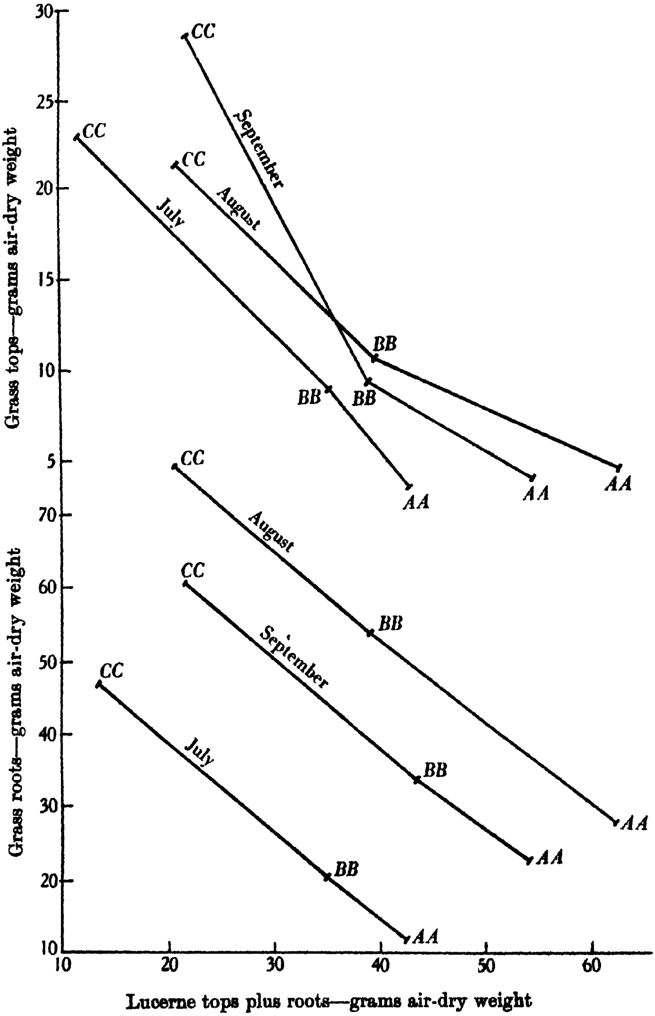

Fig. 9. Lucerne air-dry weights plotted against grass tops and roots. (AA, BB and CC.)

within 3 months of sowing suggests the excretion of nitrogen compounds by the latter, since no decay of the lucerne roots was apparent.

Evidence from numerous field experiments (*e.g.* Dorsey (5), Lyon (6)) in which growth of a non-legume population was assisted by the presence of a legume has suggested an excretion of nitrogenous material from the roots of the latter (cf. J. G. Lipman (1, 2)). The mode of this transfer from legume to non-legume has been but little investigated, and until quite recently its existence has been inferred rather than demonstrated. Stallings (7) postulated such a transfer of a water-soluble nitrogen compound—possibly ammonia. Joshi (8) recorded an effect upon non-legumes supposed to be due to secretions of legume nodule bacteria.

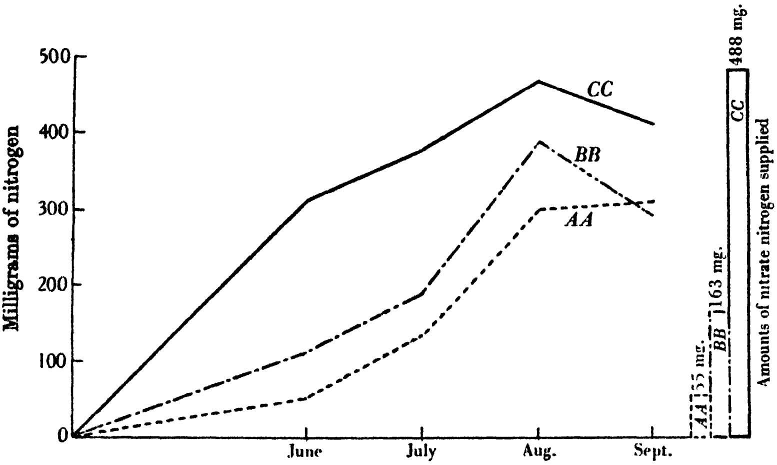

Fig. 10. Nitrogen content of grass tops and roots together.

The question has been investigated in some detail by Virtanen and his co-workers (9, 10, 11, 12, 13, 14). They grew peas, inoculated but otherwise sterile, in sand, and found that the sand contained an amount of combined nitrogen of the same order as did the peas themselves. This nitrogen, which was largely in the form of free amino-acids (9), could be profitably utilised by not more than two oat plants grown in association with each pea. See review by Nicol (16).

VIII. DISCUSSION.

The doses of nitrate applied in this experiment were small, representing in the three series 2·75, 8·15, and 24·4 parts of nitrogen per million of sand, respectively. The sand itself contained inappreciable amounts of combined nitrogen. These applications did not materially affect the crop obtained when lucerne was grown alone.

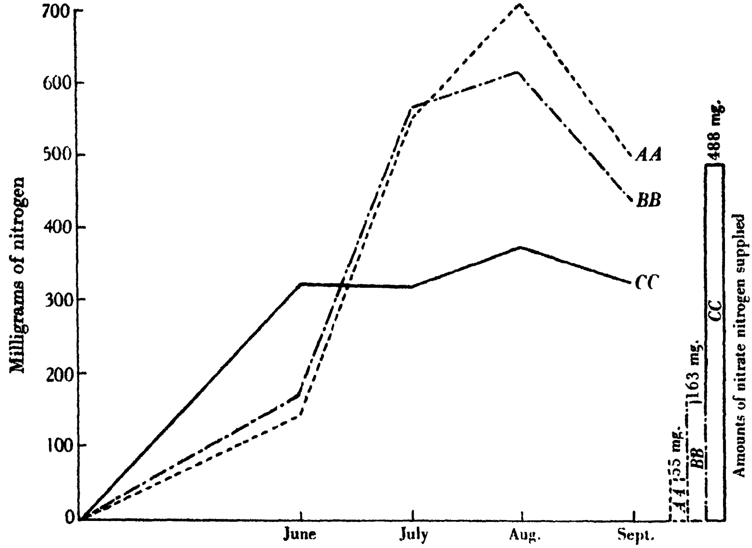

Fig. 11. Nitrogen content of lucerne tops and grass tops together.

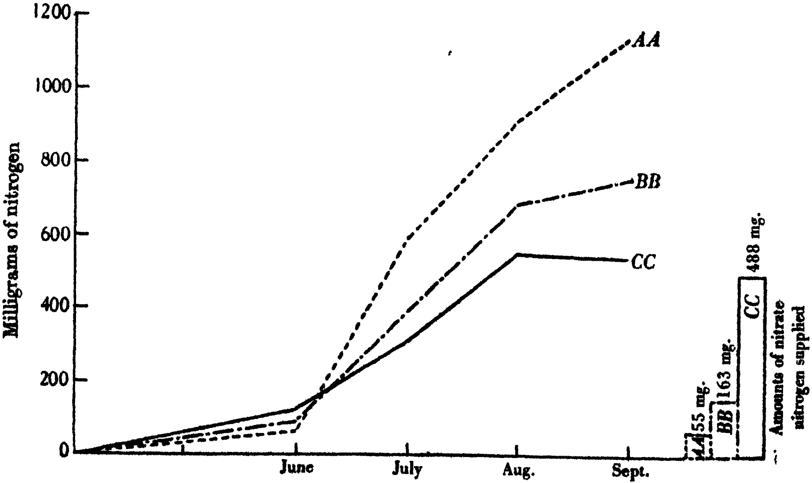

Fig. 12. Nitrogen contents of lucerne roots and grass roots together.

When the lucerne was grown with Italian rye grass, however, the two higher dressings considerably reduced the nitrogen content of the crop obtained from the combined lucerne and grass (Fig. 11). They also had a similar effect in reducing the quantity of nitrogen stored in the roots (Fig. 12).

The results of the experiment thus show that dressings of nitrate when applied to lucerne that is grown together with a non-legume may have a harmful effect, reducing both the protein content of the crop and also the quantity of combined nitrogen left in the soil to benefit the succeeding crop.

IX. SUMMARY AND ABSTRACT.

1. Inoculated lucerne was grown alone and in association with Italian rye grass, in pots of sand watered with food solution and given three different doses of sodium nitrate.

2. The dose of nitrate did not affect the dry weight or nitrogen content of lucerne when grown alone, save that the highest dose checked the root growth somewhat.

3. When lucerne and Italian rye grass were grown in association, the growth of the grass varied directly with the dose of nitrate applied, and the growth of the lucerne varied inversely to it. Checking of the lucerne growth was probably due to root competition with the grass.

4. The nitrogen contents of the combined lucerne and grass tops and that of the combined roots were also inversely related to the quantity of nitrate applied.

5. There was evidence that within 3 months of sowing the grass had obtained nitrogen fixed by the lucerne nodules.

ACKNOWLEDGMENT.

The authors' thanks are gladly accorded to Miss Sheila Arnold for her assistance in making measurements in the greenhouse and weighings in the laboratory.

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NUTRITIVE VALUE OF LUCERNE.

II. INVESTIGATIONS INTO THE INFLUENCE OF SYSTEMATIC CUTTING AT THREE DIFFERENT STAGES OF GROWTH ON THE YIELD, COMPOSITION AND NUTRITIVE VALUE OF LUCERNE.

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Introduction.

In a previous communication (1) the writers gave an account of an investigation, carried out during the season of 1932, into the changes of composition, both organic and inorganic, which the lucerne crop undergoes as it passes through the different stages of growth up to flowering. Four separate crops of lucerne, growing in different localities on widely varying types of soil, were dealt with in these trials, which embraced the investigation not only of the first growths, but also of the later growths of these crops. Attention was also directed to the securing of data for the yields at the times when the different cuts were taken. In addition, a preliminary attempt was made to elucidate the question of the nutritive value of lucerne, this being limited, however, to the carrying out of three digestion trials, the first and second of these dealing with the digestibility of the first growth of lucerne at the stages of bud and flower respectively, whilst the third dealt with the second growth at the stage of flower. The results threw a definite light on the feeding value of green lucerne at the budding and flowering stages and enabled conclusions to be drawn respecting the relative feeding values of lucerne at these stages of growth and of grass submitted to certain systems of grazing or cutting.

In view of the significance of these conclusions in relation to the utilisation of lucerne and pasture herbage in the fresh condition, and also to the industrial processes of lucerne and grass-drying by artificial means, it was desirable that they should be confirmed by the carrying out of further digestion trials on other crops of lucerne in a more systematic manner than was possible during the preliminary season of 1932. This therefore has formed the primary object of the experiments to be described in the present communication. Investigations of the composition, digestibility and nutritive value of the first, second and third growths of lucerne have been made under conditions of systematic cutting at the stages of (1) bud and (2) flower. In addition, a determination of the digestibility and nutritive value of first-growth lucerne in its pre-budding stage of growth has also been made.

Account has been kept during the season's work of the effect of cutting lucerne systematically at certain definite stages of growth, namely, pre-budding, budding and flowering, on the yields per acre of dry matter, starch equivalent and digestible protein, and on the health and vigour of the crop. Although the results obtained in these several respects will be cited in this paper, it is realised that several seasons of such work may be necessary before it is possible to pronounce finally on the question as to which is the earliest stage at which lucerne can constantly be cut without injuring the plant and shortening the life of the stand.

The season (1933) during which the present work was carried out was characterised by the prevalence of long periods of heat and drought. Heat and sunshine were experienced as early as late March and the first part of April, but the tendency to early spring growth was largely counterbalanced by the coldness of the nights and the unusual dryness of the soil. Heat and drought were again encountered in May and the early days of June, although abundant rainfall was registered during the remainder of June. Much of July and almost the whole of August were given over to intense heat and drought, the dry weather lasting almost unbroken until September 11. The season of 1933 was one of the driest, sunniest and hottest summers on record. Some conception of the unusual conditions may be formed from the summary of the meteorological data recorded in Table I, although the rainfall totals in themselves do not perhaps adequately reflect the extreme dryness of the season. Most of this rainfall was registered during a few short spells of wet weather which interrupted the course of the drought.

Table I. *Meteorological review of season* 1933.

	April	May	June	July	Aug.	Sept.
Total rainfall in inches	1·44	1·83	1·80	1·69	0·94	1·69
Total sunshine in hours	161·0	151·3	249·2	249·8	237·6	185·2
Mean max. daily temp., ° F.	57·8	62·8	69·6	75·7	76·8	69·6
Mean min. daily temp., ° F.	39·8	45·3	48·8	55·2	54·3	50·4

In view of the reputation of lucerne for being able to withstand the effects of drought, the present season's results have a special interest, in that they afford an insight into the influence of prolonged drought on the yield, feeding value and general well-being of the crop. It has moreover been possible to secure a quantitative comparison between the behaviour of pasturage and lucerne under the influence of such extreme meteorological conditions.

I. COMPOSITION AND NUTRITIVE VALUE OF LUCERNE WHEN CUT AT THE PRE-BUDDING STAGE OF GROWTH.

Although, as will be shown in a later section of this paper, it is undesirable, from the standpoints of yield and vigour of the crop, that lucerne should be submitted to systematic cutting in its pre-budding stage of growth, it must sometimes happen that the stock-feeder, in utilising the crop for feeding in the green condition, finds himself in the position of cutting part of the early-seasonal growth for this purpose before it has actually arrived at the bud stage. It is desirable, therefore, that information respecting the digestibility of lucerne at the pre-budding stage should be available, especially in view of the probability that lucerne, like grass, displays its highest digestibility in the earliest stages of growth.

The material for the digestion trial was cut from a one-year-old stand of lucerne (variety Provence). Since further data about this crop will be given in later sections of this paper, it may be noted that the seed (not inoculated, since lucerne had been grown on this site before) was drilled on June 1, 1932 at the rate of 25 lb. per acre, the spacing between the rows being 7 in. The field was situated on the light gravelly soil that characterises the higher part of the Howe Hill University Farm at Cambridge. Manurial treatment was restricted to the application of 4 cwt. of superphosphate of lime per acre. The lucerne had favourable weather and germinated well. It grew very satisfactorily and was mown, cutting rather high, in early September. During the spring of 1933, the crop was given neither manurial nor mechanical treatment. It displayed early growth and in the latter part of April, when the pre-budding digestion period was begun, it had a green, healthy appearance, the plants varying from 10 to 18 in. in height. At the end of the period of feeding on May 10, the plants had reached a height of 17–24 in., but no buds had as yet appeared.

Two pure-bred Suffolk wethers, aged about 2 years at the beginning of the present season's feeding experiments, were used for the purpose of the digestion trials. The daily ration consisted of 6000 gm. of pre-budding lucerne fed in the long condition on the day of cutting. The crop was scythed so as to leave a 2–3 in. stubble, after which signs of active recovery were displayed within 5–7 days. The mean dry matter of the crop as fed to the sheep was as low as 14·64 per cent. The sheep, when brought from the pasture to the metabolism room, were badly "scoured." After being given the usual "worming" treatment, they were gradually brought on to the lucerne diet, and it was notable that despite the moistness and succulent character of the young lucerne, the faeces from both sheep became almost straightway perfectly firm and rounded.

In Table II are recorded the data for the composition of the pre-budding lucerne (dry matter basis), for the digestion coefficients of the constituents of the lucerne (mean for two sheep) and for the digestible composition and nutritive value of the lucerne (dry matter basis). The full details of the digestion trial, however, are shown in the tables in the appendix to this paper. Reference to these detailed data shows that the results for the individual sheep in this period of feeding displayed an excellent degree of harmony.

Table II. *Showing results of investigation into the feeding value of first-growth pre-budding lucerne* (*one-year-old stand at Howe Hill*, 1933).

(1) Crude composition (dry matter basis)	%
Crude protein	25·33
Ether extract	2·35
N-free extractives ...	38·13
Crude fibre	22·12
Ash	12·07
Silica	0·86
Lime (CaO)	2·98
Phosphoric acid (P_2O_5) ...	0·88
Chlorine (Cl_2)	0·36
True protein	18·24
"Amides"	7·09

(2) Digestible composition (dry matter basis)	%
Digestible crude protein	21·28
„ ether extract	0·89
„ N-free extractives	30·43
„ fibre	14·09
„ organic matter	66·69
Starch equivalent ...	59·81
Nutritive ratio	2·19

(3) Summary of digestion coefficients (mean for 2 sheep)	%
Dry matter ...	73·3
Organic matter	75·9
Crude protein ...	84·0
Ether extract ...	38·0
N-free extractives	79·8
Crude fibre ...	63·7

Comments on Table II.

Detailed comparison of the results for the pre-budding cut of lucerne with those for the budding and flowering cuts will be given in a later section of this paper. It will be shown that lucerne resembles grass in displaying its highest digestibility at the earliest stage of growth, at which stage also the dry matter of the crop is richest in starch equivalent and digestible protein.

Of immediate interest is the question as to the relative feeding values of pre-budding lucerne and young grass, since in the previous communication (1) it was demonstrated that lucerne, both in the stages of bud and flower, is very distinctly inferior in digestibility and nutritive value to pasture herbage submitted to systems of regular cutting at intervals varying from 1 to 5 weeks. This difference in digestibility was shown to be particularly marked in the case of the fibre, which in pasture herbage is non-lignified and of high digestibility, but in lucerne is woody and of low digestibility. On account of its high content of indigestible fibre (arising from the woody nature of the stems) and its relatively low content of digestible organic matter and starch equivalent, it was concluded that lucerne, both in bud and in flower, is comparable in nutritive properties to a superior coarse fodder rather than to the pasture cuts, the dry matter of which has the character of a concentrate. It is now possible to extend this comparison to pre-budding lucerne, the necessary data being set out in Table III.

Table III. *Comparison of nutritive values of pre-budding lucerne, pasture herbage and meadow hay* (*dry matter basis*).

			Pasture herbage					
	Meadow hay (2) (very good quality)	Pre-budding lucerne	Fortnightly cuts (3)			Monthly cuts (4)		
			Extreme values		Mean	Extreme values		Mean
	%	%	%	%	%	%	%	%
Crude protein	13·8	25·3	21·3	27·9	23·5	17·2	23·5	19·4
Crude fibre	25·8	22·1	12·9	17·2	15·9	17·7	24·3	21·2
Digestion coefficients of:								
Crude protein	63·2	84·0	78·8	81·7	—	75·3	82·1	—
Ether extract	46·4	38·0	51·9	66·6	—	33·2	55·9	—
N-free extractives	67·1	79·8	80·0	85·6	—	78·6	87·1	—
Crude fibre	63·0	63·7	80·3	82·3	—	78·6	84·9	—
Total organic matter	64·6	75·9	78·0	82·3	—	76·7	83·4	—
Digestible protein	8·7	21·3	17·1	20·8	18·8	13·0	19·3	14·7
Digestible organic matter	59·3	66·7	70·2	74·5	72·2	70·0	75·6	72·5
Starch equivalent	45·2	59·8	67·8	73·8	69·9	64·3	70·6	67·1

The data in Table III show that pre-budding lucerne, considered on the basis of dry matter, is very definitely superior in digestibility and nutritive value to a very good grade of meadow hay. The most striking features of the lucerne figures are the high crude protein content (25·3 per cent. of the dry matter), the remarkably good digestibility of this constituent (84 per cent.) and consequently the high percentage of digestible protein (21·3 per cent. of the dry matter). Pre-budding lucerne is clearly equal in these respects to young grass in its phases of highest protein content and digestibility. The digestion coefficient of the N-free extractives (79·8 per cent.), which is comparable in magnitude with the corresponding figure for young grass, is also noteworthy.

Nevertheless, taking the data as a whole, lucerne, even in its pre-budding stage of growth, is not equal to the fortnightly or monthly pasture cuts in digestibility and nutritive value. This inferiority is reflected in the values for the starch equivalents, that for lucerne being 59·8 per cent. (dry matter basis) as against values ranging from 64·3 to 73·8 per cent. for the pasture cuts. The difference is mainly to be attributed to the digestibility of the fibre in the lucerne, which, though definitely higher than that for the fibre in budding or flowering lucerne, is distinctly lower than that for the fibre in the pasture cuts. That this should be so in the case of the monthly pasture cuts is specially significant, since during the flush period of growth, most of the grasses in a pasture are able, under a system of monthly cuts, to reach the early flowering stage, *i.e.*, a stage of growth far in advance of that represented by pre-budding lucerne.

It would seem, therefore, that the main distinction in nutritive properties between lucerne and grass is the readiness with which the young lucerne plant produces fibre, and the early stage of growth at which the fibre begins to display signs of lignification and diminished digestibility. The fact that the protein and N-free extractives of the lucerne show no correspondingly early running-off in digestibility suggests that this development and lignification of fibre is taking place mainly in the stems, and not to any significant extent in the leaves of the plant. It is obviously to these processes that lucerne owes its habit of erect growth. In grass, on the other hand, lignification of the fibrous constituent is postponed to a much later stage of growth than is the case with lucerne. This difference, which occasions very largely the observed differences between lucerne and grass from the nutritive standpoint, may be related to the different habit of growth of grass, which in the early stages is not erect and upstanding as with lucerne.

It will be noted from Table III that 100 lb. of the dry matter of pre-budding lucerne contains 59·8 lb. of starch equivalent, including 21·3 lb. of digestible protein. Clearly the dry matter of the plant at this stage approximates more closely to the protein-rich concentrate than to the coarse fodder. It may be regarded as a concentrate of rather moderate starch equivalent, but furnishing a generous supply of digestible protein. In respect of this latter constituent, it compares with the dry matter of young grass at its best, but it is inferior as a source of starch equivalent. A lucerne meal made by the artificial drying of pre-budding lucerne would contain, assuming a moisture content of 8 per cent., 55 per cent. of starch equivalent, including 19·6 per cent. of digestible protein. As an illustration of the concentrate character of such a meal, it can be shown that 4 lb. of a mixture of 2 parts by weight of the pre-budding lucerne meal with 1 part of maize meal would supply 2·51 lb. of starch equivalent, including 0·63 lb. of digestible protein; *i.e.* the nutrient matter necessary for the production of 1 gallon of milk containing 3·7 per cent. of fat.

Despite this satisfactory finding, however, it is extremely doubtful whether it would be feasible to cut lucerne continuously at the pre-budding stage for the purpose of manufacturing lucerne meal, and even if this could be done without injury to the stand, whether it would be economic from the standpoint of yield to do so. This matter will be referred to again in a later section.

II. COMPOSITION AND NUTRITIVE VALUE OF LUCERNE CUT SYSTEMATICALLY AT THE STAGES OF (1) BUD AND (2) FLOWER.

Investigations into the influence of cutting lucerne systematically at different stages of growth on the composition and nutritive value of the crop were carried out during the 1933 season on a 2-year-old stand of lucerne (variety Provence) growing on heavy "skirt" land at Willingham, Cambridgeshire. A description of this crop, together with the treatment that it has received in the previous seasons of its growth, was given in a previous communication relating to yield and composition trials (1). In the spring prior to the present investigation, the crop was given the usual mechanical treatment, but no fertilisers were applied. A number of large-scale contiguous plots were marked out for the purpose of investigating the influence of different systems of cutting on the yield and vigour of the stand. It will not be necessary to describe the lay-out of these plots in this paper, since obviously a satisfactory answer to the question as to how the life of the stand is affected by the system of cutting can only be arrived at by continuing the work over a number of seasons. It will be convenient therefore to postpone giving the detailed plan until a final report on the question is possible, and for the present to focus attention on the results obtained, during the 1933 season, from

Table IV. *Composition, on basis of dry matter, of two-year-old lucerne cut systematically at the stages of (1) pre-bud, (2) bud and (3) flower (Willingham, 1933).*

	By cutting successive growths at the										
	(1) Pre-budding stage					(2) Budding stage			(3) Bloom stage		
No. of growth	1	2	3	4	5	1*	2*	3*	1*	2*	3
Date of cutting	May 4	May 29	June 28	July 19	Aug. 16	May 28–June 6	July 2–July 11	Aug. 10–Aug. 19	June 12–June 21	July 27–Aug. 5	Sept. 1
Average height of crop...	13 in.	14 in.	12 in.	12 in.	8 in.	24 in.	21 in.	26 in.	38 in.	32 in.	16 in.
	%	%	%	%	%	%	%	%	%	%	%
Crude protein	27·86	32·59	26·72	29·63	23·83	20·65	22·43	21·41	17·08	19·31	21·54
Ether extract	3·43	3·09	2·38	3·00	2·95	2·19	2·59	2·25	1·64	2·47	2·36
N-free extractives	38·74	35·43	38·90	39·32	43·13	40·73	39·36	40·30	41·23	39·91	42·10
Crude fibre	20·65	17·49	22·30	17·83	18·44	28·01	26·05	25·40	29·92	28·82	22·32
Ash	9·32	11·40	9·70	10·22	11·65	8·42	9·57	10·64	10·13	9·49	11·68
True protein	18·32	21·92	20·24	24·30	18·56	15·35	17·67	17·31	12·51	14·93	17·44
"Amides"	9·54	10·67	6·48	5·33	5·27	5·30	4·76	4·10	4·57	4·38	4·10
SiO_2-free ash	8·78	9·94	9·54	10·03	11·42	8·29	9·30	10·30	9·51	9·43	11·63
Lime (CaO)	3·25	2·98	3·64	3·68	4·65	3·51	3·34	4·00	4·01	3·64	4·61
Phosphoric acid (P_2O_5)	0·87	1·13	0·74	0·99	0·64	0·63	0·70	0·57	0·44	0·57	0·52
Chlorine (Cl_2)	0·28	0·35	0·25	0·30	0·20	0·15	0·19	0·25	0·37	0·25	0·34
Dry matter as cut	17·90	14·00	19·40	19·70	30·40	21·74	20·90	24·91	24·88	25·56	25·70

* Represent composite samples from digestion trials.

Table V. *Composition, on basis of dry matter, of one-year-old lucerne cut systematically at the stages of (1) pre-bud, (2) bud and (3) flower (Howe Hill, 1933).*

	By cutting successive growths at the										
	(1) Pre-budding stage				(2) Budding stage			(3) Bloom stage			
No. of growth	1	2	3	4	1	2	3	1*a**	1*b**	2	3
Date of cutting	Apr. 27	May 25	June 23	July 17	June 1	June 26	July 25	June 9	June 9	July 20	Aug. 17
Average height of crop...	16 in.	16 in.	15 in.	6–15 in.	34 in.	22 in.	21 in.	42 in.	42 in.	14–29 in.	24 in.
	%	%	%	%	%	%	%	%	%	%	%
Crude protein	24·42	29·57	25·63	26·10	19·11	24·28	20·63	18·00	15·89	19·53	19·88
Ether extract	3·77	3·69	3·96	4·09	2·56	3·00	3·52	2·51	2·17	2·98	2·69
N-free extractives	41·48	33·88	37·41	38·38	39·29	35·55	38·16	39·04	39·56	37·51	38·27
Crude fibre	18·67	16·52	20·71	18·89	28·12	24·38	25·82	29·62	31·54	29·17	27·48
Ash	11·66	16·34†	12·29	12·54	10·92	12·79	11·87	10·83	10·84	10·81	11·68
True protein	18·99	22·38	19·93	20·83	14·52	18·91	16·74	13·22	11·45	15·86	15·76
"Amides"	5·43	7·19	5·70	5·27	4·59	5·37	3·89	4·78	4·44	3·67	4·12
SiO_2-free ash	11·03	12·20	11·72	12·10	10·77	11·90	11·60	10·35	10·58	10·65	11·54
Lime	2·53	3·15	3·35	3·47	3·19	3·40	3·65	3·43	3·51	3·34	3·64
Phosphoric acid	0·90	1·06	0·79	0·87	0·66	0·88	0·69	0·58	0·53	0·66	0·59
Chlorine	0·44	0·48	0·55	0·56	0·44	0·56	0·43	0·42	0·34	0·51	0·67
Dry matter as cut	17·35	13·54	17·40	18·83	21·18	14·72	20·00	24·90	40·80	24·53	23·60

* 1*a* represented normal growth; 1*b* drought-affected.
† High ash and silica content due to contamination with soil.

three of the plots, namely, those which were subjected to simple systematic cutting at the stages of (1) pre-bud, (2) bud and (3) flower.

In Table IV are given the data for the composition, on the basis of dry matter, of the various lucerne samples which were obtained from the three differently-treated plots. As is indicated in the table, digestion trials were carried out on all the budding cuts and on two of the flowering cuts, so that in these cases the data represent the composition of composite samples made up to be representative of the lucerne cut day by day over the periods shown in the date column. In addition to the Willingham data, a corresponding set of figures is given in Table V for the several pre-budding, budding and flowering cuts obtained from a series of plots marked out on the one-year-old lucerne growing on the light gravelly soil of the Howe Hill University Farm. It was on this crop that the investigation into the composition and nutritive value of pre-budding lucerne, described in the preceding section of this paper, was carried out. The writers are indebted to Mr A. Eden for the carrying out of this particular set of analyses.

Comments on Tables IV and V.

Before discussing the significance of the data in Tables IV and V, it should be pointed out that the figures in every case refer to the composition of the *weed-free* samples of lucerne. A detailed discussion was given in the previous communication (1) of the manner in which the composition of lucerne varies with the stage of growth at which the crop is cut. Much fuller mineral analyses of the samples were carried out in this initial investigation, as in addition to the lime, phosphoric acid and chlorine estimations made in the present trial, determinations of potash, soda, ferric oxide, magnesia, organic and inorganic sulphur were also made. The reader is therefore referred to the first publication for a detailed study of this phase of the question. It will merely be necessary in this communication to indicate how far the present data are in harmony with the conclusions drawn from the results of the earlier trials; to inquire whether the successive growths of lucerne, subjected to systematic cutting at a particular stage of growth, display uniformity in respect of organic and mineral composition, and, if not, to discover what are the characteristic variations; and further, in view of the exceptionally dry character of the 1933 season, to attempt to decide how the composition of lucerne is affected by severe drought.

General conclusions respecting composition of lucerne. It will be advisable, for the sake of brevity, to enumerate without further discussion those conclusions from the 1932 investigation (1) which are clearly borne out by the results of the present trial. (1) With increasing maturity, lucerne suffers a progressive diminution in respect of its content of crude protein. Contemporaneously with this change, the fibre content of the crop undergoes a corresponding increase. (2) Lucerne is already rich in fibre at the bud stage, but at the stage of bloom it is as fibrous as grass that has reached the hay stage of maturity and very much more fibrous than pasture herbage grown under systems of weekly to 5-weekly cutting. (3) Despite its reputation as a source of protein, lucerne in bud and flower does not excel the pasture cuts in this respect. Further, the proportion of "amides" in the crude protein of lucerne at all stages of growth is considerably higher than is the case with the pasture cuts. (4) Lucerne is richest in ether extract in its pre-budding stage of growth, but at all stages is poorer than the pasture cuts in this respect. (5) Lucerne is definitely richer than the pasture cuts in SiO_2-free ash, displaying in particular a very high lime content. The latter increases as the crop progresses in maturity, whereas the phosphoric acid, which is highest in the pre-budding stage of growth, shows an opposite variation.

In comparing the results in Tables IV and V for the two different crops of lucerne investigated during the present season of experiment, it may be observed that although the crops were growing on such different types of soil, the one light and gravelly and subject to fairly quick drying out in a droughty season like 1933, the other heavy and moisture-retentive, the data for the corresponding cuts show, in respect of organic composition and content of lime and phosphoric acid, a good degree of similarity. Only in the chlorine content is there any significant difference, the Willingham samples being poorer in this respect than the Howe Hill samples. The conclusion recorded in the previous communication may be cited in this connection, namely, that differences in manurial treatment and soil conditions may lead to significant modifications of the mineral composition of the lucerne crop, particularly in respect of lime and chlorine content (1).

Influence of drought on growth and composition of lucerne. It would be anticipated, when seeking to trace the effect of drought on the composition of lucerne, that such influence would be more evident in the Howe Hill data than in the Willingham results, because of the differences in soil conditions. The one-year-old lucerne on the light gravelly soil at Howe Hill suffered severely in the hot, dry weather, the effect being striking to the eye on June 9, when the first flowering cut was taken.

An intense heat-wave and drought of about 10 days' duration had disclosed pronounced soil irregularities in the experimental area. On numerous small patches, characterised by shallowness of soil, the flowering lucerne had turned brown or bleached in the leaf, the latter having become dry and brittle. The weeds in these small areas were yellow and shrivelled. Sharply contiguous with these patches of wilting lucerne were areas in which the flowering plants were showing scarcely any ill-effects from the drought. Two samples were accordingly cut at this stage, one consisting of normal growth (1*a*) and the other of drought-bleached plants (1*b*). These were analysed separately.

It will be seen from Table V that the dry matter content of the normal lucerne was 24·9 per cent., whereas that of the drought-affected sample had risen to the very high value of 40·8 per cent. Apart from this, however, the only distinction that has the appearance of significance is the lower protein content of the wilted lucerne (15·9 per cent. of the dry matter as against 18·0 per cent.), although it is possible that the slightly higher fibre content is also an effect of the desiccation occasioned by the drought. No significant differences between the two samples are detectable in respect of mineral composition, although a consideration of the lime data as a whole (Tables IV and V) suggests that a continuance of drought tends to raise the lime content of lucerne to a higher level. This is particularly brought out by the data for the drought-affected pre-budding growth 5 from the Willingham crop. The dry matter content of this sample was, for pre-budding lucerne, abnormally high at 30·4 per cent., whilst the lime content, on the basis of dry matter, displayed an equally sharp rise to 4·6 per cent. This sample was the poorest of all the pre-budding cuts in respect of crude protein.

It is of interest to consider these findings in relation to those for pasture herbage. The main effects of severe drought and the consequent "browning" of pasture herbage have been found to be: (1) a pronounced reduction of moisture content; (2) a very decided falling-off in the percentage of protein; (3) a slight increase in the percentages of N-free extractives and crude fibre; (4) an abrupt rise in the percentage of lime, accompanied by a decline in the percentage of phosphoric acid (4).

Despite satisfactory rainfall in the second half of June and also over the period July 7–16, the further progress of the Howe Hill lucerne was very disappointing. Recovery on the affected areas was very slow, and the vigour of the crop as a whole was seriously affected by the long spells of intense heat, sunshine and drought which, apart from the aforementioned short periods, characterised the second half of the 1933 season right up to mid-September. The lucerne plants on the affected areas were dwarfed and stunted, and consequently the whole field had an extremely patchy appearance. On August 17, for example, when the last flowering cut was taken, the normally-growing plants had attained a height of about 24 in. and were in half-flower; a sample of this section of the crop showed a dry matter content of 23·6 per cent. On the affected areas, however, the crop was very backward, being no more than 3–6 in. high and not yet having arrived at the bud stage. The smallness of the yield in this section of the crop was partly counterbalanced by the high dry matter content of the stunted plants, which had reached the very high value of 47·4 per cent.

The section of the crop devoted to systematic cutting at the pre-budding and budding stages suffered so severely in the drought that it was not possible to secure any samples for analysis after July 17 (pre-budding plots) and July 25 (budding plots). It should be pointed out, however, that the prolonged drought did not lead actually to the dying-out of any part of the crop. Under the influence of the rains of September, the lucerne displayed an irregular recovery. An inspection on October 10 showed that the whole area had become green again, the plants in the better parts having reached a height of 12 in., whereas in the affected areas the crop was about 6 in. high.

Lucerne is said to give the best results on light and fairly dry soils. The observations outlined above emphasise the conclusion that if lucerne is to maintain its reputation for enduring drought, such soils must in addition be *deep* and not easily dried out. To attempt to grow lucerne on a light and fairly shallow soil is to court partial failure of the crop in a dry season.

As might be anticipated, the Willingham lucerne, growing on a heavy, water-retentive soil, did not feel the effects of the drought so severely as was the case with the Howe Hill crop. Indeed, this excellent stand of lucerne displayed a remarkable capacity for sustaining a fresh, green growth despite the abnormally hot and droughty character of the season. Nevertheless, signs of the disadvantageous influence of the drought were not lacking in the later part of the season. No cuts from the pre-budding and budding plots could be obtained later than August. On September 1, only the flowering plots displayed sufficient growth for sampling purposes. Recovery on this plot, however, had been somewhat tardy and irregular. The crop had barely reached the flowering stage. Most of the plants were about 16 in. high, with some small patches up to 20 in., but here and there were small areas of stunted growth where the plants, though beginning to flower, were only 4–5 in. in height. The growth on this plot, which on the whole had still a surprisingly green, healthy appearance, was not abundant enough for the purposes of a digestion trial, and it was consequently cut for yield and analytical purposes only. It will be noted (see Table IV) that the dry matter of the sample (25·7 per cent.) was not unusually high. The crude protein content (21·5 per cent. of the dry matter) was not very different from what might be expected for a third growth in very early flower. The only other special features of the composition of this drought-affected sample were the very low fibre content (22·3 per cent. of the dry matter) and the very high lime content (4·6 per cent.).

Distinguishing characteristics of successive growths of lucerne. It was concluded from the results of the 1932 lucerne trials that the third growth of lucerne was consistently richer in protein than the first and second growths. The present season, owing to the complicating effects of the summer drought, was not so favourable to the investigation of the features which may distinguish the successive growths obtained under any particular system of cutting. Despite this circumstance, however, certain noteworthy differences were observed. An inspection of the data in Table IV shows, for example, that the composition of the second pre-budding growth was strikingly different from that of the other pre-budding cuts. This growth displayed the lowest content of dry matter, the highest content of crude protein and "amides," the lowest content of fibre and the highest content of phosphoric acid. That this difference was not fortuitous is shown by the fact that the second pre-budding growth from the Howe Hill crop displayed the same characteristics (see Table V). Further, at the time of cutting the second growth, the disturbing effects of drought had not come into play.

The question arises as to why the second growth of pre-budding lucerne should possess these special characteristics. Its high protein and low fibre content suggests that it may have been leafier than the other growths. Determinations of the leaf-stem ratio of the successive pre-budding growths showed that this was actually the case. In the case of the Willingham crop, for example, the leaf-stem ratios (*i.e.* the ratio of the weights of leaf and stem dry matter as determined on a representative sample of pre-budding plants) were 1·41, 1·59 and 1·44 respectively for growths 1, 2 and 3. The corresponding values for the Howe Hill crop were 1·40, 1·51 and 1·34. This explanation would further account for the high phosphoric acid content of the second growth, since systematic analyses of leaf and stem separately have shown that the leaf is invariably richer than the stem in respect of both phosphoric acid and lime, a conclusion which is illustrated by the data in Table VI for the first three pre-budding growths from the Willingham crop.

Table VI. *Lime and phosphoric acid content of leaf, stem and whole plant (dry matter basis).*

	Stem		Leaf		Whole plant		
Willingham, 1933	CaO %	P_2O_5 %	CaO %	P_2O_5 %	CaO %	P_2O_5 %	Leaf-stem ratio
First pre-budding growth (May 4)	2·13	0·70	4·26	1·05	3·25	0·87	1·41
Second pre-budding growth (May 29)	2·52	0·94	3·12	1·23	2·98	1·13	1·59
Third pre-budding growth (June 28)	2·27	0·59	4·40	0·95	3·64	0·74	1·44

The extra leafiness of the second growth cannot, however, be the whole explanation, since if this were the case, the lime content of this growth should be higher than that of the first and third growths. Actually, however, it was lower. The data in Table VI show that this was due to a big drop in the lime content of the leaf of the second growth, which more than offset the slightly higher lime content of the stem. Since a low lime content and a high phosphoric acid content are indexes of immaturity in the lucerne crop, it must be concluded that the real explanation of the special characteristics of the second pre-budding growth is that this growth (14 in. high) represented a more immature phase of development than either the first or third growths (13 in. and 12 in. high respectively).

The tendency of the later growths in the season to display an enhanced leafiness was shown, despite the complications introduced by the drought, by the higher leaf-stem ratios of the fourth and fifth Willingham pre-budding growths, which were 2·15 and 1·86 respectively. In the case of the fourth growth, this rise in the leaf-stem ratio was accompanied by an increased content of crude protein (29·6 per cent. of the dry matter), but for the final growth, the crude protein (23·8 per cent.) was the lowest recorded for all the pre-budding growths. This late-seasonal fall was undoubtedly an effect of the droughty weather, the percentage of crude protein in the leaf, on the basis of dry matter, having fallen to 28·4 per cent., compared with 36·9 per cent. in the case of the second pre-budding growth. The exceptionally high lime content of this final growth (4·65 per cent. of the dry matter) must also be attributed to the influence of drought, the value for the leaf having risen as high as 5·2 per cent.

It is not so easy, in the case of the budding and flowering growths, to disentangle the effects associated with the period of the season from those of the drought on the chemical composition of the successive growths. The tendency to increased leafiness with the advance of the season, however, is again brought out, the leaf-stem ratios for the first, second and third Willingham budding growths being 0·94, 1·06 and 1·28 respectively, whilst the ratios for the first two flowering growths were 0·73 and 1·07 respectively. Similar differences were also noted for the successive Howe Hill budding and flowering growths.

An inspection of Tables IV and V shows that the second growths of both budding and flowering lucerne were somewhat richer in crude protein and poorer in fibre than the first growths. As a consequence of the droughty weather, however, the extra richness in protein, found in the previous year's work to be characteristic of the third growth, was not generally noted. Only in the case of the final flowering growth at Willingham was a significantly increased protein and decreased fibre content observed; but the crop at this stage was only 16 in. high (compared with 30–40 in. for the first and second growths) and in very early flower. In other respects, also, this final growth was obviously abnormal as a result of drought influence, and its high lime content (4·6 per cent. of the dry matter) must probably be attributed to this factor rather than to an effect associated with the lateness of the season.

Observations made on the several lucerne crops subjected to investigation in this and the previous season have led to the conclusion that the first growth progresses more slowly through the different stages of development and comes up to flower more tardily than the later growths. This probably explains why the farmer frequently cuts the first growth for hay before it has actually come into flower, since by so doing he is more assured of securing the maximum possible number of later cuts. Further, if the first growth is allowed to occupy the land until it is in flower, there is often danger of its becoming "laid" and consequently difficult to cut satisfactorily with the horse-mower. Such was the case with the present Howe Hill lucerne, the main part of which was mown for hay at the stage of bud to obviate the manifest danger of its becoming too badly "laid" for successful cutting. This risk is not usually to be feared with the later growths, since the results of these investigations, so far as they have gone, suggest very clearly that, in an ordinary season, the first growth gives the heaviest yield of lucerne.

RESULTS OF DIGESTION TRIALS.

With the object of securing data respecting the starch equivalent and digestible protein content of the different Willingham lucerne cuts, five digestion trials were carried out, three being conducted on the budding cuts and two on the first and second flowering growths. As a consequence of the retardation of growth by the drought, no feeding trial was possible on the final flowering growth, the amount of lucerne available in this case being insufficient for the purpose. Two pure-bred Suffolk wethers, aged about 2 years at the beginning of the experiments, were employed in the digestion trials, the daily ration consisting of 6000 gm. of lucerne fed in the long condition on the same day as it was cut.

Table VII. *Digestibility and nutritive value of lucerne at different stages of growth.*

	Season 1933						Season 1932 (1)		
No. of period ..	1	2	3	4	5	6	7	8	9
Date of cutting ..	Apr. 29–May 10	May 28–June 6	July 2–July 11	Aug. 10–Aug. 19	June 12–June 21	July 27–Aug. 5	June 7–June 17	July 2–July 11	Aug. 4–Aug. 14
Stage of growth ..	Pre-bud	Bud	Bud	Bud	Flower	Flower	Bud	Flower	Flower
No. of growth ..	1	1	2	3	1	2	1	1	2
	%	%	%	%	%	%	%	%	%
Digestion coefficients of:									
Crude protein	84·0	79·8	80·1	77·9	75·9	79·4	75·8	74·5	75·3
Ether extract	38·0	20·4	19·6	5·3	14·0	19·0	25·3	9·8	20·0
N-free extractives	79·8	75·6	72·2	73·7	66·8	73·7	74·2	70·2	75·7
Crude fibre	63·7	49·6	47·6	47·0	44·7	45·4	46·3	42·6	37·5
Total organic matter	75·9	67·3	65·6	64·8	60·2	64·4	65·7	60·4	62·0
On basis of dry matter:									
Digestible crude protein	21·28	16·48	17·97	16·68	12·96	15·33	15·49	12·96	14·55
„ ether extract	0·89	0·45	0·51	0·12	0·23	0·47	0·66	0·20	0·45
„ N-free extractives	30·43	30·79	28·42	29·70	27·54	29·41	31·33	27·62	29·50
„ fibre	14·09	13·89	12·40	11·94	13·37	13·08	11·08	12·66	10·70
Total digestible organic matter	66·69	61·61	59·30	58·44	54·10	58·29	58·56	53·44	55·20
Starch equivalent	59·81	51·51	50·08	48·66	42·46	47·28	50·81	42·44	44·76
Nutritive ratio	2·19	2·77	2·34	2·51	3·20	2·84	2·84	3·14	2·83

A very striking observation in connection with lucerne-feeding which has been noted consistently in these investigations is the perfect firmness of the faeces from rations consisting wholly of lucerne, even when the crop is fed in a very early stage of growth (see the previous section on the feeding of pre-budding lucerne). In only one trial has any deviation from this behaviour been observed, namely, in the period when the third budding growth was being tested, sheep XVII in this case being slightly "scoured." The usual depressing effect of this condition on the digestibility of the protein and ether extract was noted (see the tables in the appendix). Sheep XVIII was not affected in the same way, however, and it was concluded that the condition of the other sheep was probably due to the effect of the hot weather on the animal itself rather than to some peculiarity of the lucerne consequent on growth under droughty conditions.

The complete details of the digestion trials are given in the tables in the appendix, whilst the composition of the several lucerne composite samples has already been recorded in Table IV. The data respecting the digestibility and nutritive value of the lucerne cuts are summarised in Table VII. For convenience of comparison, the results for pre-budding lucerne (see the previous section) and those for the budding and flowering cuts of the previous year (1) are also included in the table.

Comments on Table VII.

The data for periods 1, 2 and 5 illustrate clearly the manner in which the digestibility and nutritive value of lucerne run off as the crop advances in maturity. The reduction in digestibility of the fibrous constituent is most marked, but the effect is shown by the other constituents also, although in the case of crude protein, the digestion coefficient still remains very high even at the flowering stage. The digestion coefficients of the total organic matter afford the best index of these changes, the values diminishing from 75·9 to 67·3 and finally to 60·2 per cent.

Over this period of growth, the nutritive ratio widened from 2·2 to 3·2, the percentage of digestible protein declining from 21·3 per cent. of the dry matter in the pre-budding stage to 13 per cent. in the stage of bloom. The percentage of total digestible organic matter also fell from 66·7 (pre-bud) to 61·6 (bud) and 54·1 per cent. (bloom), whilst the corresponding changes in the value of the starch equivalent (dry matter basis) were from 59·8 to 51·5 and finally to 42·5 per cent.

A comparison of the results for periods 5 and 6 suggests that the second growth of the lucerne in flower was slightly superior to the first flowering growth in respect of digestibility and nutritive value. In both cases the digestibility of the crop was determined at approximately the same stage of flowering (early bloom to half bloom), and in neither case was the crop significantly affected by the dry weather. It will be noted from Table VII that the digestion coefficients of every constituent of the second flowering growth were slightly higher than the corresponding values for the first growth, the value for the total organic matter, for example, being 64·4 as against 60·2 per cent. In addition, the second growth was richer in digestible protein (15·3 per cent. of the dry matter as against 13 per cent.), digestible organic matter (58·3 as against 54·1 per cent.) and starch equivalent (47·3 as against 42·5 per cent.).

It has already been shown that the second growth was leafier than the first growth, as is evidenced quantitatively by the relative leaf-stem ratios for the two growths. This difference obviously accounts for the observed superiority of the second growth in digestibility and nutritive value, and it is interesting to note that a similar finding was noted in the 1932 lucerne trials (see Table VII).

Turning to the three successive budding growths (periods 2, 3 and 4), it is seen that the characteristic differences described above for the successive flowering cuts are not to be noted. Indeed, the data for digestibility and nutritive value in Table VII indicate that the first budding growth was slightly superior in these respects to the two later growths, despite the circumstance that a contrary behaviour might have been anticipated on the basis of the evidence of the leaf-stem ratios. It may be that the characteristic variations found to occur in the successive flowering cuts are not revealed at the earlier stage of budding growth, but it appears more feasible to assume that the conditions of heat and drought attendant on the carrying out of the digestion trials of the second and third growths, particularly the third growth, may have led to a slight depression of the digestibility of these growths and thus have prevented the characteristic variations of digestibility and nutritive value among the successive budding cuts from being brought out.

A comparison of the 1932 and 1933 results (see Table VII) reveals a considerable degree of consistency between the two sets of data. The remarkably close agreement between the results for the first flowering cuts in the two years is particularly impressive. The significance of these similarities in the two sets of figures is enhanced by the following considerations: (1) the weather conditions of the two years were strikingly dissimilar; (2) the 1932 crop was a 4-year-old stand growing on a light gravelly soil, while the present lucerne was a 2-year-old crop on heavy land. It is fair to assume, therefore, that the results of the present investigation are confirmatory of the conclusions arrived at from the results of the earlier trials respecting the feeding value of lucerne (1). It will merely be necessary in this paper to give a brief summary of these conclusions.

Lucerne, both in bud and flower, is very distinctly inferior in digestibility and nutritive value to pasture herbage submitted to systems of cutting at intervals from 1 to 5 weeks. This difference in digestibility is particularly marked in the case of the fibre, which in pasture herbage is non-lignified and of high digestibility, but in lucerne is woody and of low digestibility. On account of its high content of indigestible fibre, arising from the woody nature of the stems, and its relatively low content of digestible organic matter and starch equivalent, the dry matter of lucerne, both in bud or in flower, is comparable in nutritive properties to a superior coarse fodder rather than to the pasture cuts, the dry matter of which has the character of a concentrate. On the other hand, the dry matter of lucerne in its pre-budding stage of growth has been shown in the preceding section of this paper to approximate more closely to the protein-rich concentrate than to the coarse fodder. In respect of digestible protein, it compares with the dry matter of young grass at its best, but is inferior as a source of starch equivalent.

III. SEASONAL YIELD OF NUTRIENT MATTER FROM LUCERNE WHEN CUT SYSTEMATICALLY AT THE STAGES OF (1) PRE-BUD, (2) BUD AND (3) FLOWER.

In Table VIII are summarised the yields of weed-free lucerne, in terms of lb. dry matter per acre, which were obtained by systematic cutting of the Willingham experimental plots at the stages of (1) pre-bud, (2) bud and (3) flower.

Table VIII. *Seasonal yields of weed-free lucerne* (*Willingham*, 1933).

By systematic cutting at the following stages:	Pre-bud lb. dry matter per acre	Bud lb. dry matter per acre	Flower lb. dry matter per acre
Growth 1	1788	3227	4125
Growth 2	680	1968	2544
Growth 3	976	1178	882
Growth 4	385	—	—
Growth 5	138	—	—
Total for season	3967	6373	7551

The data in Table VIII definitely support the finding of the 1932 investigation to the effect that lucerne, like grass, displays a diminishing intensity of productivity as the season advances (1). This behaviour was naturally accentuated in the present season by the severe summer drought. It will be noted that systematic cutting at the flowering stage produced the greatest weight of dry matter, namely, 7551 lb. of dry matter per acre. The three budding cuts gave 6373 lb. of dry matter per acre (*i.e.*, 84·4 per cent. of the yield from cutting at the flowering stage), whilst systematic cutting at the pre-budding stage, although it enabled five cuts to be obtained, produced only 3967 lb. of dry matter per acre (*i.e.*, 52·5 per cent. of the yield at the flowering stage and

62·2 per cent. of that produced by cutting the lucerne in bud). It may be observed further that allowing the crop to advance from the pre-budding to the budding stage before cutting occasioned an increase of 2406 lb. of dry matter per acre in the season's yield, whereas the increase obtained by permitting the lucerne to grow from bud to flower was much smaller, namely, 1178 lb. of dry matter per acre.

Since the protein content and digestibility of lucerne decrease with increasing maturity, it would be expected that the disparities in productivity under the three systems of cutting would not be so exaggerated when based on the production of starch equivalent and digestible protein. That this is actually the case is shown by the data in Table IX.

Table IX. *Production of nutrient matter by systematic cutting of lucerne at the stages of* (1) *pre-bud,* (2) *bud and* (3) *flower* (*Willingham,* 1933).

	By systematic cutting at the stage of		
	Pre-bud	Bud	Flower
lb. dry matter per acre	3967	6373	7551
lb. starch equivalent per acre	2468*	3221	3401
lb. digestible protein per acre	947*	1082	1076

* Calculated on the basis of the digestion coefficients of the Howe Hill pre-budding lucerne (see Table II) and the composition of the five Willingham pre-budding cuts (see Table IV).

The data in Table IX reveal the fact that although cutting at the pre-budding stage produced only 52·5 per cent. of the dry matter obtained by cutting at the flowering stage, this disparity is much reduced if the higher digestibility of the pre-budding lucerne is taken into account, cutting at the pre-budding stage yielding 72·6 per cent. of the starch equivalent, and 88 per cent. of the digestible protein obtained by cutting at the flowering stage. Similarly, although systematic cutting in bud gave only 84·4 per cent. of the dry matter obtained by cutting in flower, the yield of starch equivalent under the former system of cutting represented 94·7 per cent. of that obtained from the flowering lucerne, whilst in respect of production of digestible protein, no significant difference is to be discerned in the data recorded in Table IX.

It should be kept in mind that the foregoing data were secured in a season of unusual drought, and that the relative productivities under the three systems of cutting would probably be modified in a season of well-distributed rainfall. The information so secured, however, should be of use in helping to decide at what stage lucerne should be cut for purposes of artificial drying. But a more important consideration than yield is bound up with this question, namely, the possible injury to the plant and consequent shortening of the life of the stand by systematic cutting at too premature a stage. It is too early in these investigations to pronounce on this question as it affects the growth of lucerne in this country, although it is significant that both at Willingham and Howe Hill, the plants in the pre-budding plots were able to survive the combined effects of drought and frequent cutting. This constituted a particularly severe test in the case of the Howe Hill plots, where the adverse effects of the dry weather operated in such a marked degree, and it will naturally be of great interest to discover how these plots continue to yield under the same system of cutting during the coming 1934 season.

It is already clear, however, that frequent cutting at the pre-budding stage renders the problem of keeping down infestation by weeds and grasses much more difficult than when the crop is allowed to grow on to bud or flower, the smothering effect of the crop being exerted to a much smaller degree. Investigations of this question under American conditions have led to the following conclusions: "(1) the reduction in stand and the replacement of the lucerne by grass as a result of early and frequent cutting; (2) the fact that late or infrequent cutting does not injure the stand, but does result in a loss of leaves and a hay of lower protein content and poorer quality; (3) considering all factors, it is doubtful if any farmer can afford to cut continuously, or even generally, earlier than tenth bloom in fields which it is desired to maintain in lucerne" (5).

The possibility that injury to the stand by early cutting may be obviated by allowing at least one of the growths to reach the flowering stage is one that is being investigated in this Institute at the present time.

PASTURAGE *VERSUS* LUCERNE.

Since the writers were also engaged on work in connection with the productivity of pastures during the present season of lucerne work, it is possible to compare the influence of severe drought on the growth of lucerne with that on the growth of pastures. The comparison is all the more interesting in that both lucerne and grass were growing on heavy soils of good water-retentive capacity. The pasture data in Table X represent the yields of dry matter per acre from systematic cutting at monthly intervals. In order to secure a reasonable comparison, the yields of Willingham lucerne from the five cuts at the pre-budding stage are given.

An interesting feature of the data in Table X is the demonstration they afford of the "earliness" of pasturage compared with lucerne. The first cut of pre-budding lucerne was taken on May 4. By this date, however, two monthly cuts of pasture herbage had been secured, the combined yield from the two cuts (2641 lb. of dry matter per acre) represented almost exactly two-thirds of the total season's yield from the pre-budding cuts of lucerne.

Table X. *Comparison of seasonal yields of lucerne (five pre-budding cuts) and pasturage (monthly system of cutting) during the droughty season of* 1933.

Lucerne		Pasturage	
No. and date of cut	lb. dry matter per acre	No. and date of cut	lb. dry matter per acre
First cut (May 4)	1788	First cut (late March)	1537
Second cut (May 29)	680	Second cut (April)	1104
Third cut (June 28)	976	Third cut (May)	996
Fourth cut (July 19)	385	Fourth cut (June)	550
Fifth cut (Aug. 16)	138	Fifth cut (July)	444
		Sixth cut (Aug.)	192
		Seventh cut (Sept.)*	—
		Eighth cut (Oct.)	412
Total for season	3967	Total for season	5235

* Owing to drought, no grass was available when the September cut should have been made.

The summer drought caused a very pronounced depression of the productivity of both the lucerne and the pasturage. No further cut of lucerne was possible subsequent to the meagre yield obtained on August 16. In the case of the pasture, growth had entirely ceased during September, but a recovery was shown during October as a consequence of rainfall during the second half of September. It is usually feasible to continue the periodic cuttings of pasture herbage later into the season than is the case with lucerne, since it is advisable with lucerne to allow the late growth to die down in order to furnish protection for the crowns during winter.

Over the entire season the pre-budding lucerne produced 3967 lb. of dry matter per acre, including 2468 lb. of starch equivalent and 947 lb. of digestible protein. Assuming for monthly-mown pasture herbage, on the dry matter basis, 67 per cent. of starch equivalent including 14·1 per cent. of digestible protein (4), the season's yield from the pasture totalled 5235 lb. of dry matter per acre, including 3507 lb. of starch equivalent and 738 lb. of digestible protein. The pre-budding lucerne, therefore, produced substantially less starch equivalent than the monthly-mown herbage, but, owing to its richness in digestible protein, the season's yield of this constituent from the lucerne was distinctly higher.

The foregoing comparison is based on the yield from lucerne cut systematically at the pre-budding stage, but from the practical standpoint the comparison should have greater significance if based on the production of nutrient matter from lucerne cut at a more mature stage. Such comparative data are set out in Table XI. It should be pointed out that the 1932 lucerne data refer to the yield from an initial cut at the stage of advanced bud followed by two cuts in flower, whereas the 1933 data refer to the yield from three flowering cuts.

Table XI. *Yields of lucerne from Willingham crop* (1932 *and* 1933) *compared with yields of pasture herbage from heavy-land pasturage under system of intensive fertilising and monthly cutting.*

	lb. dry matter per acre	lb. starch equivalent per acre	lb. digestible protein per acre
Pasture herbage (1930)	7996	5357	1127
„ (1931)	8274	5547	1167
„ (1932)	6714	4498	947
„ (1933)	5235	3507	738
Willingham lucerne (1932)	7191	3425	1164
„ (1933)	7551	3401	1076

It may seem curious that the yield of lucerne in terms of dry matter during the exceptionally droughty 1933 season was somewhat heavier than was obtained during the previous season, since in the case of the grass, the effect of the differing rainfalls of 1932 and 1933 is very distinctly reflected in the yields for these two years (see Table XI). The anomaly is only an apparent one, however, and is partly attributable to the circumstance that the early part of 1933 was much more favourable to growth of lucerne than the corresponding part of 1932, in which year the spring was cold and late, and partly to the fact that whereas in 1933 the first cut was delayed until the flower stage, that in 1932 was taken when the crop was still in bud. For both these reasons, the yield from the first cut in 1933 was very much higher than in 1932 (4125 lb. against 3412 lb. of dry matter per acre), a difference that went very far towards counteracting the effect of the summer drought in reducing the yield from the final cut in 1933 (882 lb. against 1404 lb. of dry matter per acre in 1932). A contributory cause may have been an increase in the early-season vigour of the lucerne crop in 1933 as compared with 1932, the extra year in the life of the stand (sown in 1931) having possibly led to a stronger establishment of the plants.

Despite the somewhat higher yield of lucerne dry matter during the 1933 season, there was very little difference between the two years' yields when the comparison is made in terms of starch equivalent. In respect of yield of digestible protein, the figure for 1932 is higher than that for 1933, this finding having an obvious explanation in the taking of the first and highest-yielding cut at a distinctly earlier stage of growth in 1932 than was the case in 1933.

The foregoing considerations demonstrate the power of lucerne to contend against the adverse influence of a dry summer, provided the crop is growing on a soil suited to its cultivation. The sensitiveness of the grass crop to unfavourable meteorological conditions is brought out by the data in Table XI. In the extremely favourable grass years of 1930 and 1931, the yields of dry matter and starch equivalent were markedly higher than for the lucerne in the years 1932 and 1933, whilst the yield of digestible protein was of the same order as for the lucerne. The less favourable season of 1932 (cold, late spring and dry June) marked a decline in the productivity of the pasture, although the yield of starch equivalent was still very much higher than for the lucerne. In the least favourable season of 1933 (intensive summer and early autumn drought) the productivity of the pasture declined still further, the yield of starch equivalent now being of the same order as for the lucerne. But there is this essential difference: the grass starch equivalent is contained in a much smaller bulk of dry matter than is the case with the lucerne, and in this more concentrated form is therefore of more value for production purposes.

In conclusion, it should be emphasised that the lucerne yield data so far brought forward by no means furnish a complete conception of the possibilities of the crop as cultivated under English conditions. It is hoped in future investigations to secure much more comprehensive data respecting the influence on the yield of lucerne of such factors as weather, soil conditions and system of cutting.

SUMMARY.

The present communication is the second contribution to the study of the nutritive characters of the lucerne crop. It deals with investigations that are the outcome of certain preliminary trials carried out in the 1932 season and reported on in an earlier communication (1). The primary object of the present trials was to investigate the composition, digestibility and nutritive value of the first, second and third growths of lucerne under conditions of systematic cutting at the stages of (1) bud and (2) flower. A determination of the digestibility and nutritive value of lucerne in its pre-budding stage of growth was also made. In addition,

account has been kept of the effect of cutting lucerne systematically at certain definite stages of growth, namely, pre-budding, budding and flowering, on the yields per acre of dry matter, starch equivalent and digestible protein, and on the health and vigour of the crop.

The season of 1933 was one of the driest, sunniest and hottest summers on record. The results therefore afford an insight into the influence of prolonged drought on the yield, feeding value and general well-being of the crop. It has moreover been possible to secure a quantitative comparison between the behaviour of pasturage and lucerne under the influence of such extreme meteorological conditions. Two separate crops were dealt with in this investigation, the first being a one-year-old stand on the light, gravelly soil of the Howe Hill University Farm at Cambridge; whilst the second, a 2-year-old stand, was situated on heavy "skirt" land at Willingham, Cambridgeshire.

The main results of the investigation may be summarised as follows: lucerne resembles grass in displaying its highest digestibility at the earliest stage of growth, at which stage also the dry matter of the crop is richest in starch equivalent and digestible protein. The dry matter of pre-budding lucerne approximates more closely to the protein-rich concentrate than to the coarse fodder. In respect of digestible protein, it is equal to the dry matter of young grass at its best, but it is inferior as a source of starch equivalent. A lucerne meal made by the artificial drying of pre-budding lucerne would contain, assuming a moisture content of 8 per cent., 55 per cent. of starch equivalent, including 19·6 per cent. of digestible protein, and 4 lb. of a mixture of 2 parts by weight of the pre-budding lucerne meal with 1 part of maize meal would supply almost exactly the requirements of starch equivalent and digestible protein for the production of 1 gallon of milk containing 3·7 per cent. of fat.

The main distinction in nutritive properties between lucerne and grass is the readiness with which the young lucerne plant produces fibre, and the early stage of growth at which the fibre begins to display signs of lignification and diminished digestibility. Lucerne, both in bud and in flower, is very distinctly inferior in digestibility and nutritive value to pasture herbage submitted to systems of cutting at intervals from 1 to 5 weeks. On account of its high content of indigestible fibre and its relatively low content of digestible organic matter and starch equivalent, the dry matter of lucerne, in bud or in flower, is comparable in nutritive properties to a superior coarse fodder rather than to the pasture cuts, the dry matter of which has the character of a concentrate.

The investigation of the composition of the numerous lucerne cuts from the two crops under experiment gave rise to conclusions substantially in harmony with those drawn from the preceding year's trials in relation to the manner in which the composition of lucerne varies with the stage of growth at which the crop is cut. The reader is referred to the text of this paper for a re-capitulation of these conclusions.

The exceedingly adverse effects of the prolonged summer drought on the growth of the one-year-old stand of lucerne on the light, gravelly and rather shallow Howe Hill soil are described in detail, and the characteristic effects of these conditions on the composition of lucerne are dealt with. The particular characteristics of drought-affected plants are shown to be a very high dry matter content and a reduced protein content, whilst a continuance of dry weather also appears to raise the lime content of the crop to higher levels. These findings are further considered in relation to the observed effects of severe drought on the composition of pasture herbage.

Lucerne is said to give the best results on light and fairly dry soils. The observations in this investigation emphasise the conclusion that if lucerne is to maintain its reputation for enduring drought, such soils must in addition be *deep* and not easily dried out. On the heavy, water-retentive Willingham soil, the crop did not feel the effects of the drought in such a severe degree. Indeed, this excellent stand of lucerne displayed a remarkable capacity for sustaining a fresh, green growth despite the hot and droughty character of the season; but even in this case, signs of the disadvantageous influence of the drought were not lacking in the later part of the season.

The results of the 1932 investigation led to the conclusion that the third growth of lucerne is richer in protein than the first and second growths. The present data also bring out certain features which seem to distinguish the successive growths of lucerne obtained under any particular system of cutting, although towards the end of the season the complications introduced by the drought prevented a decisive confirmation of the 1932 finding. It was particularly noteworthy that the second pre-budding growth of both crops was strikingly different from the other pre-budding growths, displaying the lowest content of dry matter, the highest content of crude protein and "amides," the lowest content of crude fibre and the highest content of phosphoric acid. The explanation of this finding is given in the text. The tendency of the later growths in the season to display an enhanced leafiness is clearly shown, despite the disturbing effects of the drought, by the higher leaf-stem ratios that characterised these later growths under all three systems of cutting. It is also noted that the first growth progresses more slowly through the different stages of development and comes up to flower more tardily than the later growths. The significance of this behaviour in relation to the management of the crop in farming practice is discussed in the text.

The second growth in flower was definitely superior to the first flowering growth in digestibility and nutritive value, a finding in keeping with the greater leafiness, as evidenced by the leaf-stem ratio, of the second growth. A similar finding was not noted in the case of the budding cuts. The probable explanation of this difference is given in the text.

Data are given in the final section for the seasonal yields of lucerne from the Willingham crop under the three systems of cutting. It is shown that lucerne, like grass, displays a diminishing intensity of productivity as the season advances. Systematic cutting at the flowering stage produced the greatest weight of dry matter, namely, 7551 lb. of dry matter per acre. The three budding cuts gave 84·4 per cent. of this yield, whilst the five cuts of pre-budding growth gave only 52·5 per cent. These disparities in productivity, however, are much reduced if the yields are expressed in terms of starch equivalent and digestible protein, owing to the decrease of protein content and digestibility which accompanies increasing maturity of the crop.

The problem as to whether it is advisable to cut lucerne continuously at an early stage (particularly for the purposes of lucerne meal manufacture) with a view to securing the crop at its phase of highest content of starch equivalent and digestible protein, is discussed fully in the text. Apart from the small yield obtained by cutting at the pre-budding stage, it appears probable that such treatment may injure the plants and shorten materially the life of the stand. It is hoped that investigations now in progress will furnish a complete solution of this phase of the lucerne problem. Meanwhile it may be stated that the pre-budding plots survived the combined effects of drought and frequent cutting, and their behaviour in respect of productivity under the same system of cutting will be followed in the coming season. It is already clear, however, that constant cutting at the pre-budding stage renders the keeping down of grass infestation a much more difficult problem than when the crop is allowed to grow on to bud or flower. American investigations suggest that if it is desired to maintain lucerne on the land then the crop should not be cut before tenth bloom. It will be interesting, however, to ascertain if injury by early cutting may be obviated by allowing at least one of the growths in the season to reach the flowering stage.

Data are also brought forward in this paper comparing the seasonal yields of nutrient matter from the Willingham lucerne crop with those from heavy-land pasturage subjected to a system of monthly cuts. The relative influence of the severe drought on the productivity of lucerne and pasture is also considered in the light of the data obtained in this and past seasons of work.

In conclusion, the writers gratefully acknowledge the assistance received from Mr A. Eden in certain phases of this investigation. Thanks are also tendered to Messrs V. Thurlbourn and C. Bendall, in whose experienced hands the care of the experimental animals was placed throughout the trials.

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APPENDIX.

Digestion tables.

	Sheep XVII							Sheep XVIII						
	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.
Period 1 (first growth pre-budding lucerne):														
Daily ration	878·40	772·38	222·50	20·64	334·94	194·30	106·02	878·40	772·38	222·50	20·64	334·94	194·30	106·02
Voided	230·24	182·95	36·00	13·11	62·82	71·02	47·29	238·89	190·09	35·13	12·47	72·48	70·01	48·80
Digested	648·16	589·43	186·50	7·53	272 12	123·28	58·73	639·51	582·29	187·37	8·17	262·46	124·29	57·22
Digestion coefficients (%)	73·79	76·31	83·82	36·48	81·24	63·45	55·40	72·80	75·39	84·21	39·58	78·36	63·97	53·97
Period 2 (first growth lucerne in bud):														
Daily ration	1304·40	1194·57	269·36	28·57	531·28	365·36	109·83	1304·40	1194·57	269·36	28·57	531·28	365·36	109·83
Voided	481·49	394·17	55·94	22·48	133·08	182·67	87·32	472·56	387·76	53·00	22·99	126·50	185·27	84·80
Digested	822·91	800·40	213·42	6·09	398·20	182·69	22·51	831·84	806·81	216·36	5·58	404·78	180·09	25·03
Digestion coefficients (%)	63·09	67·00	79·23	21·32	74·95	50·00	20·49	63·77	67·54	80·32	19·53	76·19	49·29	22·79
Period 3 (second growth lucerne in bud):														
Daily ration	1254·00	1133·99	281·27	32·48	493·57	326·67	120·01	1254·00	1133·99	281·27	32·48	493·57	326·67	120·01
Voided	454·17	385·12	53·88	25·44	137·60	168·20	69·05	462·80	395·38	57·93	26·79	136·39	174·27	67·42
Digested	799·83	748·87	227·39	7·04	355·97	158·47	50·96	791·20	738·61	223·34	5·69	357·18	152·40	52·59
Digestion coefficients (%)	63·78	66·04	80·84	21·67	72·12	48·51	42·46	63·09	65·13	79·40	17·52	72·37	46·65	43·82
Period 4 (third growth lucerne in bud):														
Daily ration	1479·10	1321·73	316·68	33·28	596·08	375·69	157·37	1494·60	1335·57	319·99	33·63	602·32	379·63	159·03
Voided	594·82	474·20	77·33	46·99	155·31	194·57	120·62	577·52	460·36	63·38	31·84	159·32	205·82	117·16
Digested	884·28	847·53	239·35	—	440·77	181·12	36·75	917·08	875·21	256·61	1·79	443·00	173·81	41·87
Digestion coefficients (%)	59·79	64·12	75·58	—	73·94	48·21	23·35	61·36	65·53	80·19	5·32	73·55	45·78	26·33
Period 5 (first growth lucerne in flower):														
Daily ration	1492·80	1341·58	254·97	24·48	615·48	446·65	151·22	1492·80	1341·58	254·97	24·48	615·48	446·65	151·22
Voided	631·82	535·39	62·56	21·37	206·31	245·15	96·43	625·14	532·81	60·31	20·72	202·65	249·13	92·33
Digested	860·98	806·19	192·41	3·11	409·17	201·50	54·79	867·66	808·77	194·66	3·76	412·83	197·52	58·89
Digestion coefficients (%)	57·68	60·09	75·46	12·70	66·48	45·11	36·23	58·12	60·28	76·35	15·36	67·07	44·22	38·94
Period 6 (second growth lucerne in flower):														
Daily ration	1533·60	1388·06	296·14	37·88	612·06	441·98	145·54	1533·60	1388·06	296·14	37·88	612·06	441·98	145·54
Voided	598·96	499·66	61·63	31·84	160·53	245·66	99·30	591·53	489·17	60·50	29·54	161·68	237·45	102·36
Digested	934·64	888·40	234·51	6·04	451·53	196·32	46·24	942·07	898·89	235·64	8·34	450·38	204·53	43·18
Digestion coefficients (%)	60·94	64·00	79·19	15·95	73·77	44·42	31·77	61·43	64·76	79·57	22·02	73·58	46·28	29·67

Summary of nitrogen balances.

Period	Sheep	N consumed per day gm.	N voided per day			Mean daily nitrogen balance gm.
			Faeces gm.	Urine gm.	Total gm.	
1. First growth pre-budding lucerne	XVII	35·60	5·76	25·22	30·98	+4·62
	XVIII	35·60	5·62	26·21	31·83	+3·77
2. First growth budding lucerne	XVII	43·10	8·95	29·03	37·98	+5·12
	XVIII	43·10	8·48	27·31	35·79	+7·31
3. Second growth budding lucerne	XVII	45·00	8·62	33·09	41·71	+3·29
	XVIII	45·00	9·27	30·22	39·49	+5·51
4. Third growth budding lucerne	XVII	50·67	12·37	34·18	46·55	+4·12
	XVIII	51·20	10·14	36·22	46·36	+4·84
5. First growth flowering lucerne	XVII	40·80	10·01	27·51	37·52	+3·28
	XVIII	40·80	9·65	28·87	38·52	+2·28
6. Second growth flowering lucerne	XVII	47·38	9·86	30·45	40·31	+7·07
	XVIII	47·38	9·68	28·48	38·16	+9·22

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METHODS OF EXPERIMENTATION IN ANIMAL NUTRITION.

By E. J. SHEEHY.

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(With One Text-figure.)

In a recent article on the above subject by Dunlop (1) reference was made to a method suggested by Sheehy and Senior (2) for the purpose of "making an adjustment in the weight curve, where, through accident or other cause not arising out of feeding, the weight of a particular animal on an exceptional occasion deviated widely from the general trend of its live weight record. A slight injury, for instance, would on occasion cause an animal either to lose weight or merely to maintain its previous weight for a week, thus placing the group to which it belonged at a disadvantage during that week" (2). Since Dunlop asserts that the method suggested "is based on a fallacy" by which is implied that it is inaccurate, the necessity arises, so as to prevent the formation of a wrong impression, to show that Dunlop's reasoning in this connection is based on incorrect impressions.

Fig. 1 graphically illustrates the progress of a pig whilst increasing from 40 to 200 lb. live weight (*a*)—dotted line—in the case when the increase was regular, and (*b*)—broken line—in the case of an identical pig where, through an accident, the continuous increase in live weight was interrupted for a period of a week. Sheehy and Senior claim that, because the disturbance is accidental and not connected with the food intake, allowance should be made therefor, and they suggest increasing the final weight of the pig, represented in (*b*) curve, by a quantity represented by the length of the line *AB* which in the figure is approximately 6 lb. The suggestion is based on the premise that were it not for the accident the point *B* would coincide with *A*. Dunlop claims that the figure to be added to the final live weight of the pig, represented by (*b*), curve at the termination of the test which in this case is the 20th week should be the live weight weekly increase by a 185 lb. pig which figure he fixes at 15 lb.

He says "it is well known...that the weekly gain of a pig of 40 lb. fed *ad lib.* is approximately 5 lb., while at 200 lb. the weekly gain of the same animal will have increased to 15 lb." It would be more correct perhaps to say that the weekly gains at the live weights cited are 6 and 12 lb. respectively. But according to his argument the compensation to be made in respect of the pig represented by curve (*b*) should be 15 lb. irrespective of the period of the test in which the accident and the consequent disturbance in the weight record occurred. If therefore the disturbance occurred in the 4th week, Dunlop's compensation would be

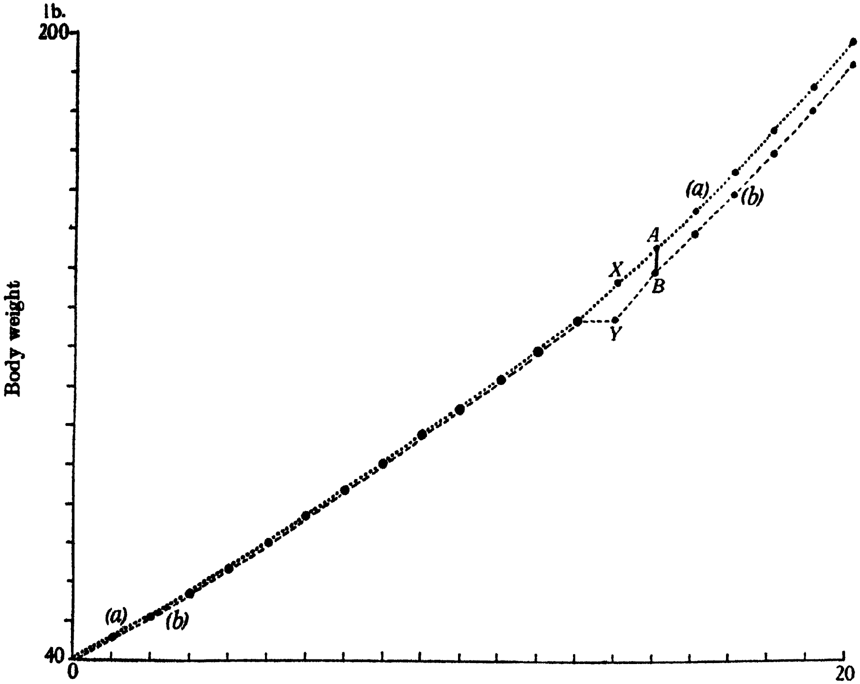

Fig. 1.

similar to that made if the interruption in the live weight increase occurred in the 18th week.

A consideration which Dunlop does not appear to have borne in mind is the enhanced live weight gain which generally occurs immediately after a suspension of progress due to some accidental disturbance. Curve (*b*)—broken line—illustrates what happens in this connection. The live weight increase for a week or two after the temporary cessation of progress is more rapid than it is immediately before or after the occurrence, and hence the point *B* is nearer to *A* than *Y* is to *X*. Therefore the pig in the course of a short time after the accident is not a full week's gain (at that period of the test) behind an identical animal whose progress had not been interrupted. The difference in weight may not exceed 60 per cent. of a week's gain (at that point in the test).

The subsequent history of the undisturbed animal—represented by curve (*a*)—and that of the pig—represented by curve (*b*)—which has had an accident is, notwithstanding the theoretical difference, for all practical purposes, similar. That is to say the curves of growth beyond *A* and *B* take an approximately parallel course, as shown in Fig. 1, and the divergence at the end of the test does not differ materially from that represented by the line *AB*.

It is contended that the method of correction suggested by Dunlop, who claims that in the case of a pig which has ceased to make gain for a fortnight "the correct method of adjustment is, of course, to allow *B* (the disturbed animal) to remain on the experiment for an extra fortnight or to add to its final live weight increase an amount corresponding to the fortnightly gain of a 185 lb. animal," would give a result which would be much further from the truth than that adopted by Senior and the writer.

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ON THE MEASUREMENT OF IMBIBITIONAL WATER.

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RECENTLY one of the authors (1) criticised the theory of the determination of the water imbibed by the soil colloids proposed by Fisher (2) on the ground that it contained several unproved assumptions, some of which are examined in the present paper. Fundamentally, the imbibitional water theory assumes that the water held by a soil can be divided into two parts, colloidally bound or imbibed water, and free water, the latter being held in the soil pores and capillaries. The method proposed by Fisher for determining the weight of water imbibed by a soil assumes that it equals the difference between the volume of water and the volume of xylene or other non-polar hydrocarbon the soil can hold in a centrifugal field of 1000 g., these volumes being calculated from the weight of the water or xylene held. This method therefore contains the following assumptions:

(1) The soil colloids do not imbibe xylene or other non-polar hydrocarbons.

(2) The imbibition of water is complete under a centrifugal field of 1000 g.

(3) The density of the liquid in the fine pores is the same as the bulk density of the liquid.

(4) The volume of the hydrocarbon held in the soil pores in the centrifugal field equals the volume of water so held.

A priori, there is no reason why the last assumption should be true, for two different processes, which work in opposite directions, can invalidate it. A soil swells on imbibing water and this swelling will probably alter the pore-space geometry of the fine pores by reducing their volume. But the surface tension of the soil-water-air interface is probably much greater than that of the soil-hydrocarbon interface, so that under a given centrifugal field there will be some capillaries and pores too large to hold the hydrocarbon but small enough to hold water.

The method employed in this investigation was to determine the weight of water and of different hydrocarbons held by the soil under two different external conditions, namely, in the moisture equivalent centrifuge against a field of 1000 g. and in the Keen-Raczkowski box. For this investigation the following four soils were used:

Barnfield Rothamsted surface soil plot 1–0, which has received 14 tons of farmyard manure every year since 1856, the sample being taken from a depth 0–6 in.

Barnfield Rothamsted subsoil from plot 8–0, which has received no manure since 1853, the sample being taken from a depth of 3–4 ft.

Gezira soil taken from the Wad Medani Experimental Station, Sudan.

Gloucester soil, from Andoversford, Gloucester, which has been formed from the weathering of an inferior oolitic limestone.

All the soil samples were taken several years ago, and have since been stored in the air-dry condition at Rothamsted. Before use they were ground to pass a 1 mm. sieve. The liquids used, with the exception of the paraffin, were obtained from the British Drug Houses, Ltd., and their description in the text corresponds with that in the B.D.H. catalogue. The paraffin used was ordinary lamp oil dried over lime. The liquids were not discarded after use, but were shaken up with lime, filtered and re-used. With the exception of the paraffin there is no evidence of any progressive change of properties, but the paraffin had to be put in contact with dry soil once before it gave steady values.

For the determination of the liquid equivalent of these soils a standard Briggs-McLane centrifuge fitted with a constant speed regulator was used. The method of working and the boxes used are the same as used by Coutts (3), the only differences being that oven-dry soils only were used, and that, since many of the liquids used were not volatile, the initial weight of soil put in the box and the weight of soil + liquid taken out of the box only were determined. Whenever a volatile liquid was used, this soil was then dried, and the weight of dry soil removed always agreed with the weight of the dry soil put in the box to within a few milligrams.

The boxes used for the Keen-Raczkowski experiment were 3 cm. in diameter and 1·6 cm. high. The filter paper was kept down by a bent piece of steel spring wire, as described by Coutts (4). The boxes were packed and over-filled with air-dry soil, put in a 110° C. oven for 18 hours, allowed to cool, gently repacked and the surplus soil scraped off. The boxes were then weighed and either put in the wetting liquid to a depth just covering the bottom of the box, or put in a desiccator to be wetted *in vacuo*. For the vacuum wetting the desiccator was evacuated very slowly on a Hyvac oil pump, to allow the air held by the soil to escape without disturbing the packing. Sufficient liquid was then let in to allow the liquid surface to touch the bottom of the box, so that the adsorbed air which was displaced by the wetting liquid could escape slowly either through the filter paper or from the soil surface. The liquid level was then raised 3–4 mm. above the bottom of the box and the soil allowed at least 12 hours to come into equilibrium with the liquid. Dry air was then let into the desiccator, the box removed, weighed, and the soil that had swollen above the top of the box sliced off. This surplus soil was then washed free from the hydrocarbon with benzene, and dried.

The drying temperature at which the soils were oven-dried appeared to be unimportant, for no differences were found within experimental error between the weight of liquid held by a soil in either experiment when it was dried for 18 hours at 105 or 110 or 120° C. In all the experiments recorded here, the soils were dried for 18 hours at 110° C.

THE EXPERIMENTAL RESULTS.

The liquid equivalents of the four soils are given in Table I; they are expressed as the volume of liquid in c.cm. held by 100 gm. of oven-dry soil against a centrifugal field of 1000 g., the volume being obtained by dividing the weight of the liquid held by its bulk density.

Table I. *The liquid equivalents of the soils.*

(Volume of liquid held per 100 gm. of soil in the moisture equivalent centrifuge.)

	Barnfield surface	Barnfield subsoil	Gezira	Gloucester	Mean
Water	25·0	37·0	40·3	27·2	—
Paraffin	14·3	17·4	10·8	11·1	13·4
Tetralin	14·8	18·1	10·6	11·4	13·7
Tetralin (purified)	15·1	18·1	10·4	12·1	13·9
Decalin (purified)	14·6	17·0	9·9	11·2	13·2
Xylene (rectified)	14·0	15·8	9·9	10·1	12·4
Xylene (sulphur-free)	12·7	16·4	9·4	10·1	12·1
Hydrocarbon mean	14·2	17·1	10·2	11·0	

The hydrocarbon equivalents are much lower than the water equivalent, and only show small deviations from one another. The lowness of the xylene equivalent is probably due to some xylene evaporating during centrifuging, and the difference between the decalin and tetralin equivalents is probably outside experimental error. No explanation of this small difference can be given, though it is unlikely that it is due to impurities in the tetralin since the purified and commercial liquids give the same equivalents.

The results for the Keen-Raczkowski box experiment are given in Table II, where, as before, the volume of liquid in c.cm. held by 100 gm.

of oven-dry soil is tabulated, the volume being calculated from the weight of liquid held on the assumption that the density of the liquid in the soil is the same as its bulk density.

Table II. *Volume of liquid held per* 100 *gm. of oven-dry soil in the Keen-Raczkowski box.*

	Barnfield surface	Barnfield subsoil	Gezira	Gloucester	Mean
Water	42·1	59·1	81·7	59·5	—
Paraffin	37·3 (38·2)	37·5 (40·7)	48·3 (44·3)	48·7 (40·0)	42·7 (40·8)
Tetralin (purified)	38·5 (38·2)	39·1 (40·0)	52·5 (44·6)	47·1 (41·0)	44·3 (40·9)
Decalin (purified)	37·4	38·0	50·6	44·3	42·6
Xylene (rectified)	36·1 (38·6)	40·2 (40·3)	50·3 (42·0)	44·0 (40·6)	42·6 (40·4)
Carbon tetrachloride (A.R.)	36·0 (36·2)	36·7 (38·7)	47·5 (38·4)	44·7 (38·7)	41·2 (38·0)
Benzene (A.R.)	37·4 (38·6)	38·6 (40·7)	48·5 (47·0)	46·5 (42·9)	42·7 (42·8)
Hexane (B.P. 67–69°)	38·9 (38·3)	39·0 (41·3)	51·1 (46·2)	47·1 (43·8)	44·0 (42·4)
Hydrocarbon mean	37·4 (38·0)	38·4 (40·3)	49·8 (43·7)	46·1 (41·2)	—

The figures in brackets give the volume of liquid held when the soil was wetted in air. The other figures are for the soil wetted *in vacuo*.

Again it is seen that the variations between hydrocarbons are small though probably outside experimental error. Wetting the soil under vacuum barely affects the volume of liquid held by Rothamsted soils but it definitely increases the volume held by the Gezira and Gloucester soils. The effect is probably due to the difference in crumb structure of the two sets of soils.

The swelling of the soils in each liquid was also determined in the Keen-Raczkowski box experiment. For ease of calculation the swelling has been defined as the weight of oven-dry soil pushed above the level of the box per 100 gm. of oven-dry soil initially in the box. Table III gives these swellings when the soils were wetted with the hydrocarbons in the presence of dry air at atmospheric pressure.

Table III. *The swelling of the soils in hydrocarbons when wetted in air.*

	Barnfield surface	Barnfield subsoil	Gezira	Gloucester
Paraffin	6·0	5·6	6·6	2·9
Tetralin	7·5	10·0	12·0	3·6
Tetralin (purified)	8·1	10·5	12·4	5·0
Xylene (rectified)	5·9	5·7	7·2	5·0
Carbon tetrachloride (A.R.)	3·9	6·8	1·7	1·6
Benzene (A.R.)	7·6	11·5	12·6	8·6
Hexane (B.P. 67–69°)	3·3	3·6	5·3	1·3

The swellings are seen to be considerable, but they are due entirely to adsorbed and entrapped air, for when the soil is wetted very slowly in a good vacuum the swelling is found to be very small, varying erratically between 0–1 per cent.

THE DISCUSSION OF THE EXPERIMENTAL RESULTS.

As pointed out in the introduction, four assumptions have to be made in determining the imbibitional water held by a soil. The first assumption is that the soil colloids do not imbibe hydrocarbons. The data presented do not prove or disprove this, but they show that if the colloids imbibe hydrocarbons they imbibe all those investigated to approximately the same extent, for the volume of hydrocarbon a soil can hold either in the centrifuge or in the box is nearly independent of the hydrocarbon used. Again, the soils do not swell when wetted with a hydrocarbon *in vacuo*. If a soil swells on wetting *in vacuo* it must imbibe some of the wetting liquid, and, alternatively, if the soil does not imbibe any liquid it cannot swell on wetting. One cannot argue, however, that because a soil does not swell on wetting it does not imbibe any of the liquid, since the imbibed liquid could fill all the micropores and even the macropores without any swelling taking place. Hence all that can be argued is that the results are in accord with the hypothesis that the soils do not imbibe any of the hydrocarbons used.

The second assumption made in the determination of imbibitional water by Fisher's method is that the imbibition of water is effectively complete under a centrifugal field of 1000 g. It is only possible to test the truth of this assumption by using the other three assumptions, namely that the soil colloids do not imbibe hydrocarbons, that the density of a liquid in the soil pores is not altered and that the volumes of water and hydrocarbon held in the soil pores under comparable conditions are equal. Under these conditions the difference between the volume of water and the volume of hydrocarbon held by the soil under comparable conditions will give the *weight* of water imbibed by the soil colloids, for these volumes were obtained by dividing the observed weight of liquid held by its bulk density. Table IV gives the weight of water imbibed by the soils in the centrifuge and in the box experiments determined by this method.

Table IV. *Imbibitional water determined from the centrifuge and from the box measurements.*

(Weight of water imbibed per 100 gm. of soil.)

	Barnfield surface	Barnfield subsoil	Gezira	Gloucester
Centrifuge	10·8	19·9	30·1	16·2
Box	4·7	20·7	31·9	13·4
Centrifuge − Box	6·1	− 0·8	− 1·8	2·8

With the exception of the Barnfield surface soil, which appears to show a much higher imbibition under the centrifugal field, the weight of water imbibed by the soils is within experimental error the same in the two experiments, showing that under a centrifugal field of 1000 g. the imbibition of water is complete.

No direct evidence is given by the data bearing either on the density of liquids in the fine crumb capillaries, or on the volume changes in the micropore space due to the imbibition water. The experiments do show that the macropore space of the soil is unaffected by this imbibition, when the macropore space is defined as the volume of the capillaries containing air under a centrifugal field of 1000 g. This can be measured by the difference between the volume of a liquid held in the box and in the centrifuge, provided no secondary effects enter. There is no evidence that any such effects enter for soils wetted with hydrocarbons or for silts wetted with water, but it is not yet possible to determine directly if any effects enter when the soil swells on wetting. Table V shows that the macropore space is the same within the limits of experimental error for all the wetting liquids used and for all the soils except the Barnfield surface soil.

Table V. *The macropore space of the soils.*

(c.c. per 100 gm. of oven-dry soil.)

	Barnfield surface	Barnfield subsoil	Gezira	Gloucester	Mean
Water	17·1	22·1	41·4	32·7	28·3
Paraffin	23·0	20·1	37·5	37·6	29·5
Tetralin (purified)	23·4	21·0	42·1	35·0	30·4
Decalin (purified)	22·8	21·0	40·7	33·1	29·4
Xylene (rectified)	22·1	24·4	40·4	33·9	30·2
Mean of the 4 hydrocarbons	22·8	21·6	40·2	34·9	29·9

THE SWELLING OF SOILS IN WATER.

It is not possible on the experimental results so far discussed to derive any further evidence concerning the validity of the assumptions necessary for calculating the *weight* of water imbibed by a given weight of soil. An estimate of the *volume* of water imbibed by a given weight of soil can, however, be made from the swelling of the soil in the Keen-Raczkowski box. Let a box of volume V c.c. hold W gm. of oven-dry soil, and let σ be the apparent density of the oven-dry soil, where $\sigma = W/V$. On wetting the soil *in vacuo* let W_s gm. of oven-dry soil be expelled above the level of the box and let W_r gm. remain in the box ($W = W_r + W_s$). Now W_r gm. have swollen from W_r/σ c.c. in the oven-dry condition to W/σ c.c. in the saturated condition, so that the swelling per gram of oven-dry soil is $W_s/\sigma W_r$ c.c. This equals the volume of liquid imbibed by 1 gm. of soil on the assumption that the volume of free water held by the soil in the box equals the volume of air in oven-dry soil, for on this assumption if a soil imbibes v c.c. of water it must swell by v c.c. Thus this method of determining imbibitional water requires, in effect, only the fourth assumption made in Fisher's method.

The mean values of $W_s/\sigma W_r$, the swelling per gram of oven-dry soil, are given in the first row of Table VI. The individual determinations of the swelling are subject to very large variations from one experiment to another, so that $W_s/\sigma W_r$ must be dependent on some unstandardised conditions occurring, of which variations in the closeness of packing of the soil are probably the most important. If the closeness of packing can affect the swelling, the fundamental assumption of this section, namely that the volume of free water held by the wet soil equals the volume of air in the oven-dry soil, can be only partially true.

The volume of the water imbibed by the soil, calculated by this method, is smaller than the weight of water imbibed, as is seen by comparing the top line of Table VI with Table IV.

Table VI. *Volume of imbibitional water held by a soil and its mean density.*

	Barnfield surface	Barnfield subsoil	Gezira	Gloucester
Volume in c.c. per 100 gm. of soil	4·1	17·9	28·2	12·8
Mean density of water $= \frac{\text{weight of imbibed water}}{\text{volume of imbibed water}}$	1·15*	1·13	1·10	1·15

* Using box data only.

If this difference is not due to an incorrect method being used to calculate the weight or the volume of the imbibed water, it must be attributed to the difference in density between free and imbibed water. The density of the imbibed water necessary to make the determinations of the volume and the weight of imbibed water consistent is given in the second row of Table VI and is found by dividing the weight of imbibed water by its volume. The weight used was the mean of the centrifuge and the box values given in Table IV, except in the case of the Barnfield surface soil, for which the box value was used.

It is not possible to decide from direct determinations if the densities of the imbibed water calculated in this way are correct, since no suitable methods are yet available. Evidence for the correctness of these values can, however, be obtained from the weight of water imbibed and the difference in the specific volumes of the soil in a hydrocarbon and water. Let a specific gravity bottle of volume V contain m gm. of oven-dry soil of specific volume σ and W gm. of water. Let the soil imbibe i gm. of water of mean specific volume δ per gram of soil, so that there are only $(W-mi)$ grams of free water of specific volume ρ in the bottle. Then the apparent specific volume Σ of the soil in water, obtained by neglecting the imbibed water, is clearly

$$\Sigma = \frac{V - W\rho}{m}.$$

If the imbibed water is allowed for, σ, the specific volume of the dry soil is given by

$$\sigma = \frac{V - mi\delta - \rho\,(W - mi)}{m},$$

so that on eliminating V, W and m from these equations it is found that

$$(\sigma-\Sigma)=i\,(\rho-\delta) \qquad \text{......(1).}$$

In this equation Σ, the apparent specific volume of the soil in water, i the weight of imbibed water and ρ the specific volume of water, can all be determined directly, but σ, the true specific volume of the dry soil, and δ, the specific volume of the imbibed water, cannot. But the specific volume of a dry soil in paraffin or other non-polar hydrocarbons will be the same as the specific volume of the dry soil in air if the paraffin or non-polar hydrocarbon has the following three properties:

(1) They are not imbibed by the soil colloids.

(2) They can penetrate into all the fine soil capillaries and so can wet the soil completely.

(3) Their density in the fine soil capillaries is the same as their bulk density.

All these properties are already postulated by the methods used to determine the weight of water imbibed by the soil. Thus, if this equality of the specific volume of the dry soil in air and in paraffin is assumed, σ is known so that δ, the mean specific volume of the imbibed water, can be calculated from equation (1).

The specific volumes of the four soils were determined in water and paraffin using the technique developed by one of the authors (5), which allows the soil to be wetted slowly in a vacuum produced by a rotary Hyvac oil pump. The results of these determinations are given in Table VII. For the determination of the mean density of the imbibitional water, the value used for the weight of water imbibed was the mean of the centrifuge and box values given in Table IV, except for the Barnfield surface soil. Evidently the values required for the mean density of the imbibed water to bring the determinations of the volume and weight of water imbibed into harmony are reasonably well supported by the indirect determination of this density from the reduction of specific volume of the soil in water from that in paraffin. At the bottom of Table VII are given the volumes of water imbibed, calculated from the weight of water imbibed when determined either in the centrifuge or in the box, and from the specific gravity determinations. These values can easily be written down by using equation (1) when it is rewritten as

Table VII. *The mean density of imbibed water.*

	Barnfield surface	Barnfield subsoil	Gezira	Gloucester
Specific volume in paraffin	0·38891	0·37489	0·37839	0·40010
Specific volume in water	0·38160	0·36626	0·36369	0·38500
Difference $= \sigma - \Sigma$	0·00731	0·00863	0·01470	0·01510
$1/\delta$ = mean density of imbibed water	1·18*	1·04	1·05	1·11
Mean density calculated from swelling (Table VI)	1·15*	1·13	1·10	1·15
Calculated volume of imbibitional water from:				
Centrifuge	10·1	19·0	28·6	14·7
Box	4·0	19·8	30·4	11·9
Observed volume of imbibitional water (Table VI)	4·1	17·9	28·2	12·8

* Imbibitional water determined in box.

$$i\delta = i - (\sigma - \Sigma),$$

for $i\delta$ is the volume of water imbibed per gram of soil. This agreement between the volume of imbibitional water determined from the swelling of the soil in the Keen-Raczkowski box and the volume calculated from the weights of water hydrocarbon held by the soil in the moisture equivalent centrifuge and the difference in specific volume of the soil in water and the hydrocarbon does lend strong support to the interpretations of the measurements which have been given here. The exceptional case of the Barnfield surface soil, however, does suggest that some other factor besides those discussed here may be important under certain conditions.

CONCLUSIONS.

Two related methods of determining the weight of water imbibed by a soil and one independent method of determining the volume of water imbibed have been discussed, and the three methods have been shown to give concordant results. The first two methods are based on the four assumptions:

(1) That soils do not imbibe hydrocarbons.

(2) The density of the liquid in the fine soil pores is the same as the bulk density of the liquid.

(3) The volume of hydrocarbon held by a dry soil equals the volume of air held by the dry soil.

(4) The volume of free water held by a wet soil equals the volume of air held by the dry soil.

For the determination of the volume of the imbibed water it is only necessary to make the last assumption.

The determinations on the weight, volume, and density of the imbibed water by these different methods are reasonably concordant for three of the soils. One of the methods does, however, give discrepant results for the Barnfield surface soil, a soil which contains large quantities of readily decomposable organic matter, for it has had 14 tons of farmyard manure applied to it annually for over 70 years. It is, of course, not possible to argue that because the determinations of the weight and volume of the imbibed water are concordant therefore all the assumptions are valid, though the validity of the first three assumptions, which are only required for one of the determinations, is rendered more probable.

The fourth assumption, however, is probably only partially true, for the amount of swelling of these soils in water appears to be sensitive to some uncontrolled factor, which is probably the closeness of packing. It is unlikely that any air can be entrapped during wetting, causing these differences in swelling, since the wetting technique appears to allow the escape of all entrapped and adsorbed air.

The tentative conclusion arrived at from these results is that the weight or volume of the water imbibed by a soil can be measured. The main limitation in this discussion has been, however, that the accuracy of the different methods is not sufficiently great to allow a consideration of the small differences usually found between one method and another.

SUMMARY.

Two methods of determining the weight and one method of determining the volume of water imbibed by a soil have been discussed. The results of these methods have been shown to be concordant by an independent method.

The tentative conclusion reached is that the weight of water a soil imbibes can be readily determined by Fisher's method or from the Keen-Raczkowski box, but that the volume of imbibed water cannot yet be directly determined accurately.

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A STUDY OF THE FASTING METABOLISM OF VARIOUS BREEDS OF HOG.

I. INTRODUCTORY: AGE, WEIGHT AND LENGTH DATA, ETC.

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(With Four Text-figures.)

THE following paper is the first of a projected series on the results of work which has been in progress in the Animal Calorimetry Department of this Institute during the past five years. Subsequent papers will deal with body temperature variations, effects of environmental temperature, metabolism, energy expenditure, etc.

The work was undertaken in October, 1928, at the instance of the late Prof. T. B. Wood, and since that time twenty-five hogs have been studied at all ages from early youth (say 50 days old) up to an age which is well beyond that to which such animals are normally kept by the producer. Observations have been made of the age, weight, length, urine and faeces passed in fasting, body temperature, metabolism, etc., under a variety of conditions of external temperature, and pigs of nine different breeds have been included. Early difficulties in the determination of the surface area of the animals and the way in which these were circumvented have already received adequate treatment in a previous publication (1).

The metabolism has been observed during fasts varying in length from 2 to 5 days, the technique being unchanged from that employed by this department for many years past (2). A description and photograph of the present apparatus is to be found in Baillière's *Encyclopedia of Scientific Agriculture* (3).

THE ANIMALS.

The pigs used throughout the work are given in Table I with the source from which they were obtained. The selection of the animal was in all cases left to the breeder, who was asked to supply a normal average pig of the breed in which he was interested. Emphasis was laid on this point, it being clearly stated that a prospective show pig was not required, but just what each breeder considered was a pig which might be taken as representative. Table I also supplies particulars as to the breed, and the lettering by which the pigs are designated will be adhered to throughout this series of publications and is the same as that employed for the pigs concerned in the paper on surface area cited above. The animals were castrated before delivery to the laboratory, and it was requested that their weight should if possible not exceed 25 lb. at that time.

RATIONS.

For all pigs except the one lettered L the ration consisted of

65 per cent.	barley meal,
25 ,,	sharps,
10 ,,	fish meal,

while pig L had

60 per cent.	barley meal,
25 ,,	sharps,
10 ,,	fish meal,
5 ,,	soya-bean meal,

which supplies a little more protein in which the ordinary 65 : 25 : 10 mixture is admittedly slightly deficient at the younger ages.

The quantity of the mixture supplied was regulated in accordance with the weight of the animals as shown in Table II. It was fed in two portions, morning and evening, under ordinary circumstances, but when the hogs had been fasting in the calorimeter for some days the ration was fed in four portions until the digestive system had resumed its functions. The quantity was estimated to provide for maintenance and growth without appreciable fattening. The reason for the extra amount supplied to pigs W–Z will appear later.

In addition the pigs were given a small amount of green stuff, usually cabbage in spring and summer; in autumn this was often difficult to obtain and swedes were supplied, while in winter it was usually necessary to fall back on mangolds for a month or two after Christmas. This however holds for all pigs. No record of the exact dates when these changes were made has been kept, a fact which later turned out to be somewhat unfortunate as the pigs from N onwards did not do so well as the previous ones and pig P developed a disease diagnosed by Col. W. A. Wood as rickets.

The vitamin content of cabbages and swedes is satisfactory, but

Table I. *Origin, etc., of pigs used in metabolism experiments*, 1928–1934.

Hog	Breed	Breeder or agent	Date of Birth	Date of Weaning	Date of Castration
A	Tamworth	Maj. C. J. H. Wheatley, Berkswell Estate, near Coventry	30. viii. 28	17. x. 28	10. x. 28
B	Gloucester Old Spot	Maj. R. J. Fuller, Great Chalfield, Melksham, Wilts	13. ix. 28	22. x. 28	11. x. 28
C	Middle White	Mr F. Farquharson, Holywell Farm, Watford	22. vii. 28	3. x. 28	3. x. 28
D	Berkshire	Mr G. Close, Guston House, Ketton, Stamford, Lincs	31. viii. 28	24. x. 28	8. x. 28
E	Essex	Mr W. A. Lyon, Foxton House, Foxton, Cambs	15. ix. 28	12. xi. 28	3. xi. 28
F	”	” ” ”	19. x. 28	5. xii. 28	1. xii. 28
G	”	” ” ”	12. xi. 28	7. i. 29	4. i. 29
H	Large Black	Mr T. E. Hooley, Dry Drayton, Cambs	9. ii. 29	26. iv. 29	23. iv. 29
J*	Wessex Saddleback	Mr R. J. W. Dawson, Temple Dinsley, Hitchin, Herts	15. viii. 29	28. ix. 29	27. ix. 29
K	Gloucester Old Spot	Mr J. F. Wright, Olton Farm, Solihull, Birmingham	8. ix. 29	30. x. 29	18. x. 29
L	Essex	Mr W. A. Lyon, Foxton House, Foxton, Cambs	6. xi. 29	21. xii. 29	16. xii. 29
M	Tamworth	Mr J. Allsup, Whittingham Farm, Preston, Lancs	28. i. 30	9. iii. 30	13. iii. 30
N	Large White	Mr A. B. Rose, Tydd St Mary, Wisbech	19. x. 30	3. xii. 30	28. xi. 30
O	Middle White	Mr F. Farquharson, Holywell Farm, Watford	20. ix. 30	25. xi. 30	30. xi. 30
P	Large Black	Mr W. Clark Jackson, Fowlmere, Cambs	7. x. 30	5. xii. 30	18. xii. 30
Q	Lincs Curly Coat	Mr H. E. Woods, Coxford Abbey, East Rudham, Norfolk	28. i. 31	9. iii. 31	6. iii. 31
R	Berkshire	Mr C. J. Twist, Burham Grove Estate Office, Burham, Bucks	12. ii. 31	13. iv. 31	19. iii. 31
S	Wessex Saddleback	Mr F. Gentle, High Street, Brandon, Norfolk	1. iii. 31	27. iv. 31	23. iv. 31
T	Essex	Mr J. R. Tinney, Church End, Rickling, Newport, Essex	4. v. 31	*ca.* 16. vi. 31	17. vi. 31
U	Lincs Curly Coat	Messrs A. Clifton and Sons, The Manor, Fishtoft, Boston, Lincs	10. v. 31	16. vi. 31	20. vi. 31
V	”	” ” ” ” ”	4. viii. 31	15. ix. 31	11. ix. 31
W	Large Black	Mr D. W. P. Gough, Pakenham Manor, Bury St Edmunds	8. viii. 32	7. x. 32	10. x. 32
X	Wessex Saddleback	Slythehurst Saddlebacks, Ltd., Ewhurst, Surrey	22. viii. 32	15. x. 32	11. x. 32
Y	Berkshire	Maj. R. B. Sidebottom, Rothamsted, Harpenden, Herts	20. viii. 32	15. x. 32	Soon after
Z*	Middle White	Capt. D. P. Lithgow, South Newington Manor, Banbury, Oxon	10. x. 32	29. xi. 32	26. xi. 32

* Presented.

mangolds are deficient (4). On the other hand, as all the pigs had more or less the same treatment in this regard, it is not thought likely that the set-back can be traced to this cause.

Table II. *Rations supplied to the hogs daily.*

Weight lb.	Pigs A–V lb.	Pigs A–V oz.	Pigs W–Z lb.	Pigs W–Z oz.
15– 25	1	0	1	2
25– 40	1	6	1	9
40– 63	1	14	2	2
63– 88	2	6	2	11
88–125	3	0	3	6
125–175	3	12	4	3
175–225	4	8	5	1
225–275	5	4	5	14
275–325	6	0	6	12
325–375	6	12	7	9
375–425	7	4	8	2
425 and over	8	0	9	0

A post-mortem examination of the livers of pigs U and V, kindly made for the writer by Mr G. Dunlop, showed that while the reserve of vitamin A was very low it was not likely to have been deficient during the experimental period, as the tendency would certainly have been downward for some time when the examination was made. According to the recent experiments of Busson (7) this presence in the liver should indicate an actual excess.

Normally the pigs were kept in the animal house at the School of Agriculture, where normal exercise was impossible. At times it proved possible to keep them out of doors, but even then only pigs N–T had any opportunity for proper outdoor exercise. In the summer and autumn of 1932 pigs N–T were given the run of a fair-sized field at the Animal Research Station with effects which will be discussed anon.

AGE AND WEIGHT.

In recording the weight and length changes with age, it is not supposed that these can have any value otherwise than as part of the basic data on which the results in subsequent papers of this series are founded; for not only were the hogs kept under somewhat adverse conditions, as noted above, but were kept without food in all about 14 to 16 times each for from 2 to 5 days during their period of growth. Moreover, they were not on a productive ration. As basic data, however, they must be put on record, and how to do this without presenting a mass of tabular material has been given careful consideration. When plotted as curves those for the different pigs lie so close together that they would be quite illegible when reproduced. The scheme of Fig. 1 has therefore been adopted. The fasting live weights of pigs A–M were first plotted against the corresponding ages, and the best mean curve run through these observations is shown by the thick line. This curve is then projected on to the straight horizontal line at 400 lb. and the deviations from this mean curve, that is the amounts in pounds by which each pig fell short of or exceeded the weight which would be expected from the mean curve to correspond with its actual age, are set off from this horizontal line vertically on an enlarged scale. Even then it will be seen that the curves become so interwoven below about 320 lb. that it is impossible to read them, and consequently it has been necessary to publish an enlargement of this part of the diagram in Fig. 2 with a still greater enlargement of the more intricate portion of this. The observations, indicated by dots, are only inserted on the largest scale diagram on which they appear, hence there is no duplication of these. The breed of hog is indicated by the type of line used as shown in the key to the figures, and letters are placed wherever convenient to indicate the precise pig concerned. Such letters are always placed *below* the line to which they refer. From these figures all the data may be read off with little trouble. Where any doubt may arise, the pig to which the observation refers is indicated in italic script. Ringed points indicate a point on both of two intersecting curves.

The reason for selecting the pigs A–M for the plotting of the mean curve was that these pigs agreed well with one another and with previous results under like circumstances. Pigs N–T on the other hand fell away markedly from the first group at ages exceeding 250–300 days, as can be clearly seen from Fig. 1, while pigs U and V trace out an intermediate course inclining, if anything, to the former group. There is only one circumstance which seems capable of accounting fully for this difference. In the autumn of 1931 the pig M was finally disposed of and the remaining pigs from N onwards were all at or below 130 lb. weight. In previous years the animal house had been kept comfortably heated, but in this year for reasons of economy this heating was largely dispensed with, meanwhile the rations and treatment of the hogs was as before. It appears therefore that pigs N–T had to use part of a ration, computed to subserve growth and maintenance only, for generating heat to keep up their body temperature in the colder surroundings. Pigs U and V were (with the exception of P) the first to go to the field at the Animal Research Station and were there fully as long as any others, and furthermore were at the time appreciably younger than pigs N–T. Hence we can only suppose that the extra fodder (grass) which they were able to eat there was more efficacious in their case than in the others. Some effect in the same direction is also noticeable in the next youngest pigs R, S and T (see Fig. 1) at 500–550 days old. That this falling off is due to vitamin lack owing to mangolds being substituted for swedes is not likely, as pigs A–M received similar treatment. The fresh air and exercise may have had some effect on U and V, but there seems little doubt that the main factor was the extra food intake due to the supply of fresh grass *ad libitum*. To test this matter further pigs W–Z were put on the slightly increased rations shown so as to provide for maintenance and growth at the lower temperature now used in the animal house, and it will be seen from Fig. 1 that these pigs are following the lines of pigs A–M as regards weight increase, although at the lower temperature and receiving similar treatment to pigs N–V as regards exercise and feeding with mangolds in winter after swedes are not obtainable. A note on the further growth of these pigs will be made in a later paper of the series.

Dr Woodman (8) finds that even with quite young grass 6–7 lb. are required to make the equivalent of 1 lb. of a mixture of middlings and maize meal for pigs, and in the case of older herbage considers Stewart's estimate of 8–10 lb. for the 1 lb. of the meal mixture to be approximately reliable. As our pigs were still fed their full meal ration when out on grass, it might be thought that they would either be unable to eat any notable quantity of this, or, alternatively, would not consume the whole of the meal ration. In point of fact they did consume the whole of it as well as what grass they grazed, which of course was not measured, and this is quite in keeping when it is remembered that our pigs were not actually receiving a full meal ration but only such amount as would provide for growth and maintenance without appreciable fattening. Hence they might quite well add to their ration an amount in terms of meal fully equivalent to the extra ration of from 4 to 8 oz. of meal which for example the pigs W–Z received.

AGE AND LENGTH.

In Fig. 3 is shown the length of the pigs measured according to the method of Hogan and Skouby (5), that is to say from the point of the withers to the root of the tail. As in the case of the weight data certain parts of the diagram are shown on an enlarged scale in Fig. 4, and the methods of indication as to breed, observations, etc., are the same as in the weight diagrams, except that in the enlargement on Fig. 3 the observation points are duplicated, as this was added later. The method of plotting, by difference from the mean, used in Fig. 1 has not been resorted to in this case as there appeared no necessity. The thick line in Fig. 3 shows the mean of the observations on pigs A–M.

It will be noticed that in this case there is considerably less difference between the pigs of the series A–M and W–Z and those of the intermediate lot N–V, though a slight effect is noticeable. The most striking fact that arises from the curves is that the time rate of increase in length of pigs A–M decreases with age, while that of increase of weight increases with age up to about 700 days. This is of no significance however, since it arises from the fact that volume $\propto$ (length)^3. This relation gives such a definite upward trend to the length-weight relation that no variations due to age or specific gravity differences are able to obliterate it.

There would seem to be little point in publishing the curve of weight against length. It follows of necessity that the falling away of the pigs N–T and to a lesser extent U and V from the mean of the earlier animals would be very noticeable in this curve, since it appears in the age-weight curve and hardly at all in the age-length curve. It follows of course that the latter group were less fat than the former, probably for the reason given earlier. No actual temperature measurements were made in the animal house as the desirability of this was not appreciated until too late, but the writer has had access to the meteorological records at the Botanic Garden, Cambridge, for all the years involved and has satisfied himself that as far as this may be determined from an averaging of the daily minima for the period October-March in each year no one winter was very much more severe than the others, the differences in these means being less than one degree. Hence we may safely assume that the difference in the heating of the house would exercise its full effect on the animals.

An examination of both sets of curves will serve to show that under the treatment they received no breed of hog stood out to any marked extent from the rest as regards performance, though, as mentioned previously, this is by no means a suitable test—the fact merely emerges incidentally.

WEIGHT LOSS IN FASTING.

Although weighings were taken at the beginning and end of experiments, the weight losses recorded are not suitable for the application of statistical methods for the following reasons: the weighbridge is not sensitive to less than about 1 lb. and the losses registered by the smaller pigs were usually less than 10 lb.; the data on the larger pigs are affected

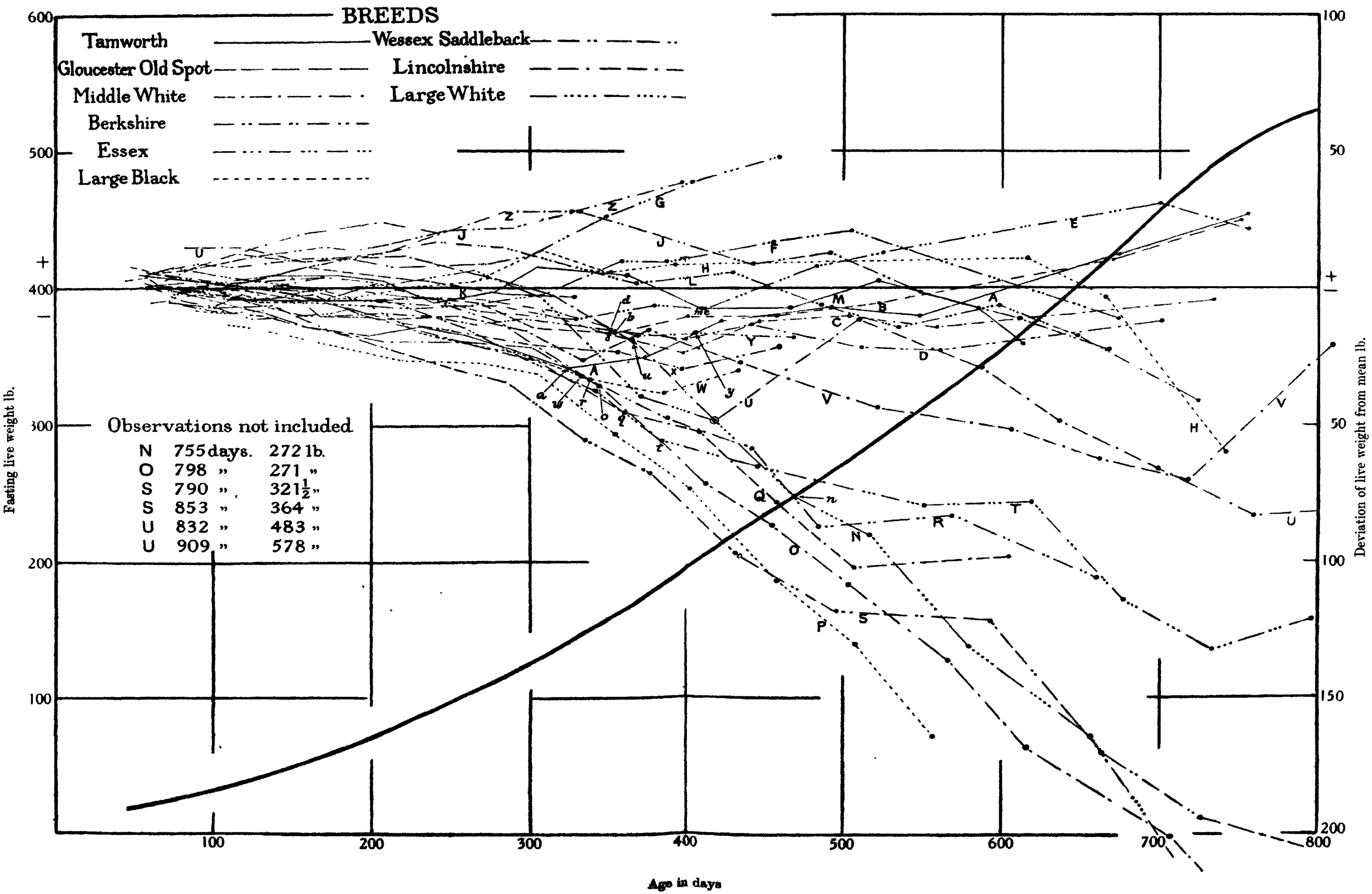

BREEDS
Tamworth
Gloucester Old Spot
Middle White
Berkshire
Essex
Large Black
Wessex Saddleback
Lincolnshire
Large White
Observations not included
N 755 days. 272 lb.
O 798 " 271 "
S 790 " 321½ "
S 853 " 364 "
U 832 " 483 "
U 909 " 578 "
Fasting live weight lb.
Deviation of live weight from mean lb.
Age in days
600
500
400
300
200
100
+
−
100
50
50
100
150
200
100
200
300
400
500
600
700
800
A B C D E F G H J K L M N O P Q R S T U V W Y Z
a b d me n o q r t u w x y

Fig. 1.

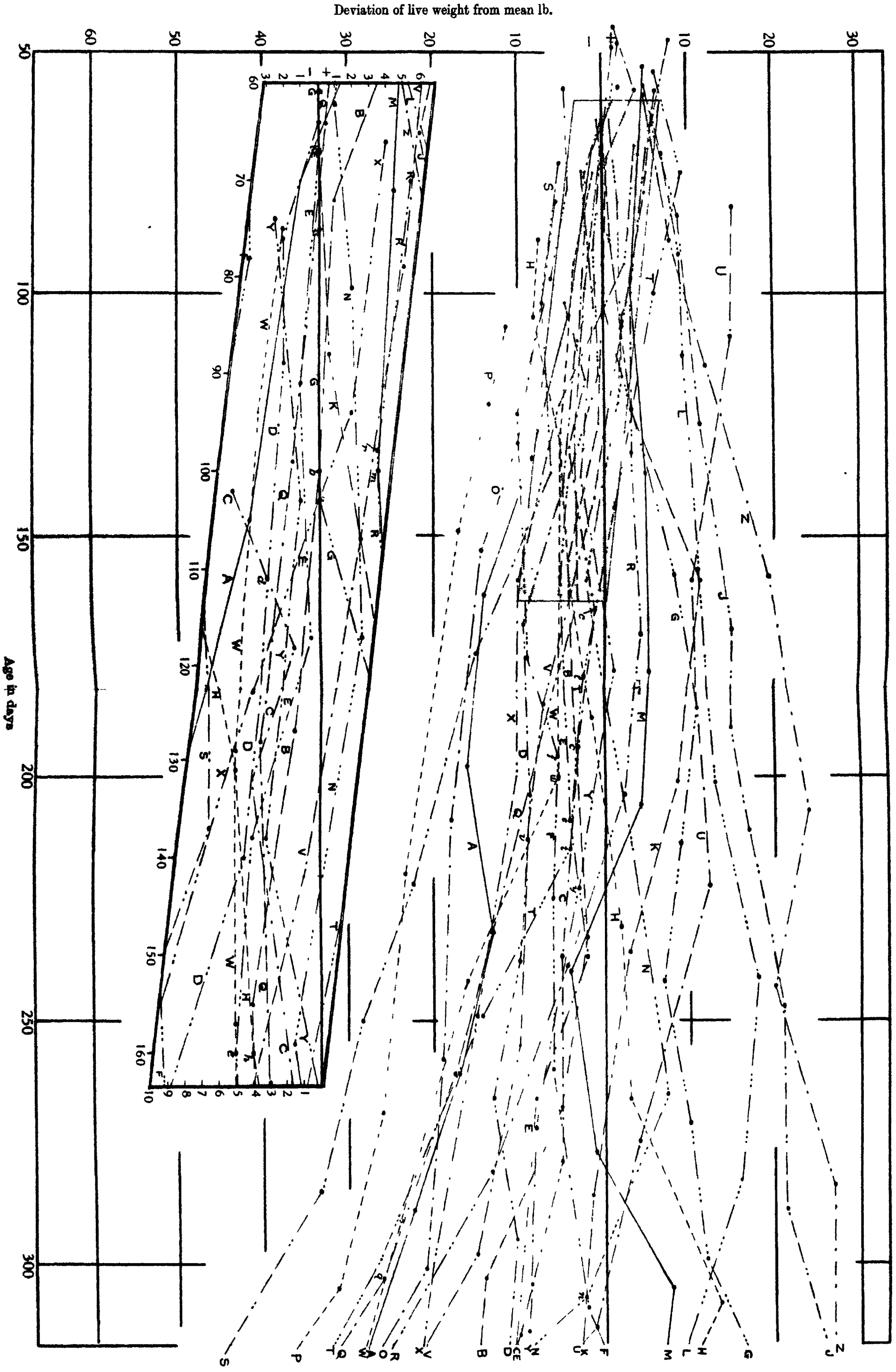
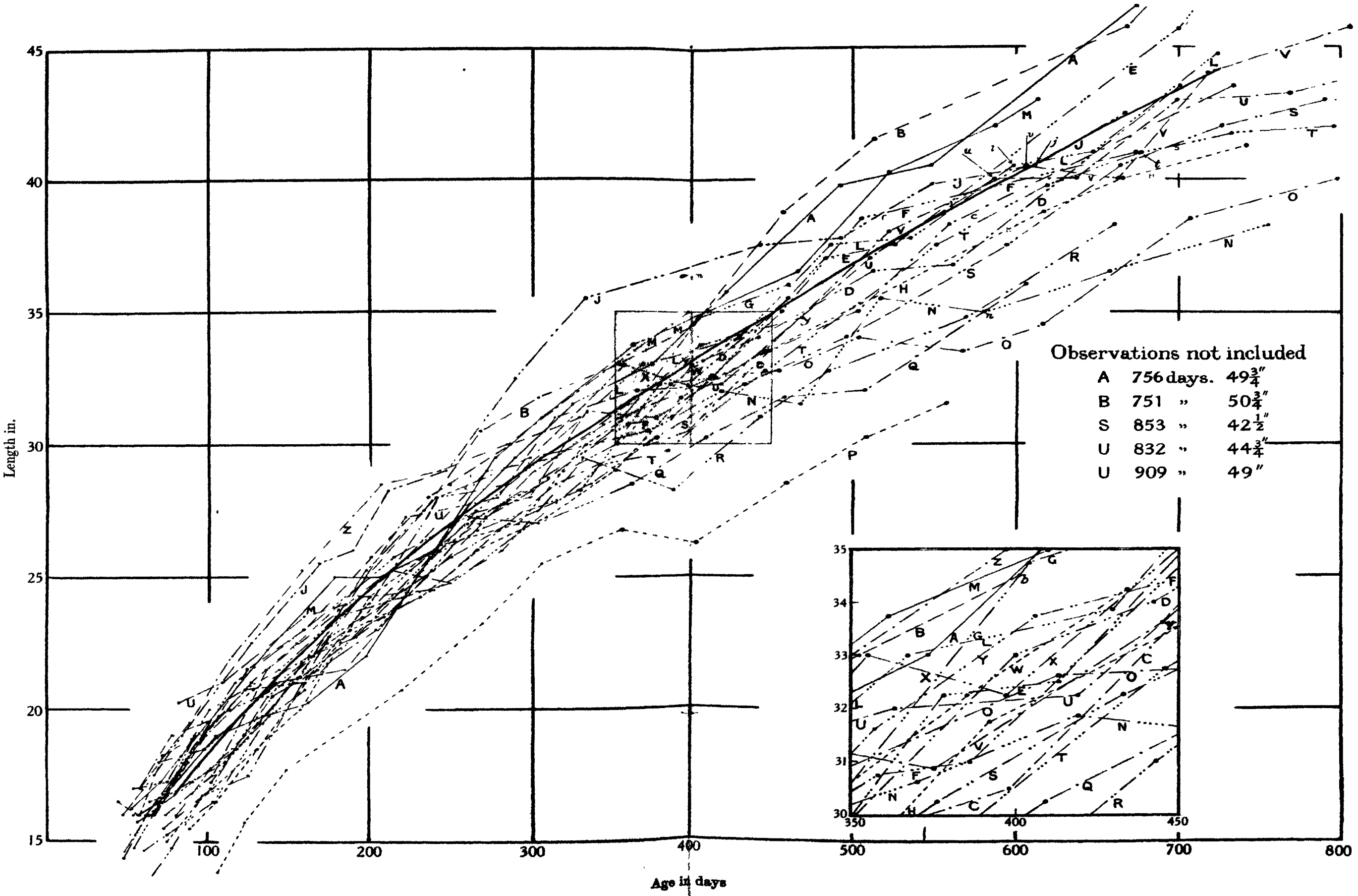

Deviation of live weight from mean lb.
60
50
40
30
20
10
–
+
10
20
30
50
100
150
200
250
300
60
70
80
90
100
110
120
130
140
150
160
S
P
T
Q
W
A
O
R
X
V
B
D
C
E
N
U
K
F
M
L
H
G
Z
J
Age in days

Fig. 2.



Observations not included

A	756 days.	$49\frac{3}{4}''$
B	751 „	$50\frac{3}{4}''$
S	853 „	$42\frac{1}{2}''$
U	832 „	$44\frac{3}{4}''$
U	909 „	$49''$

Fig. 3.

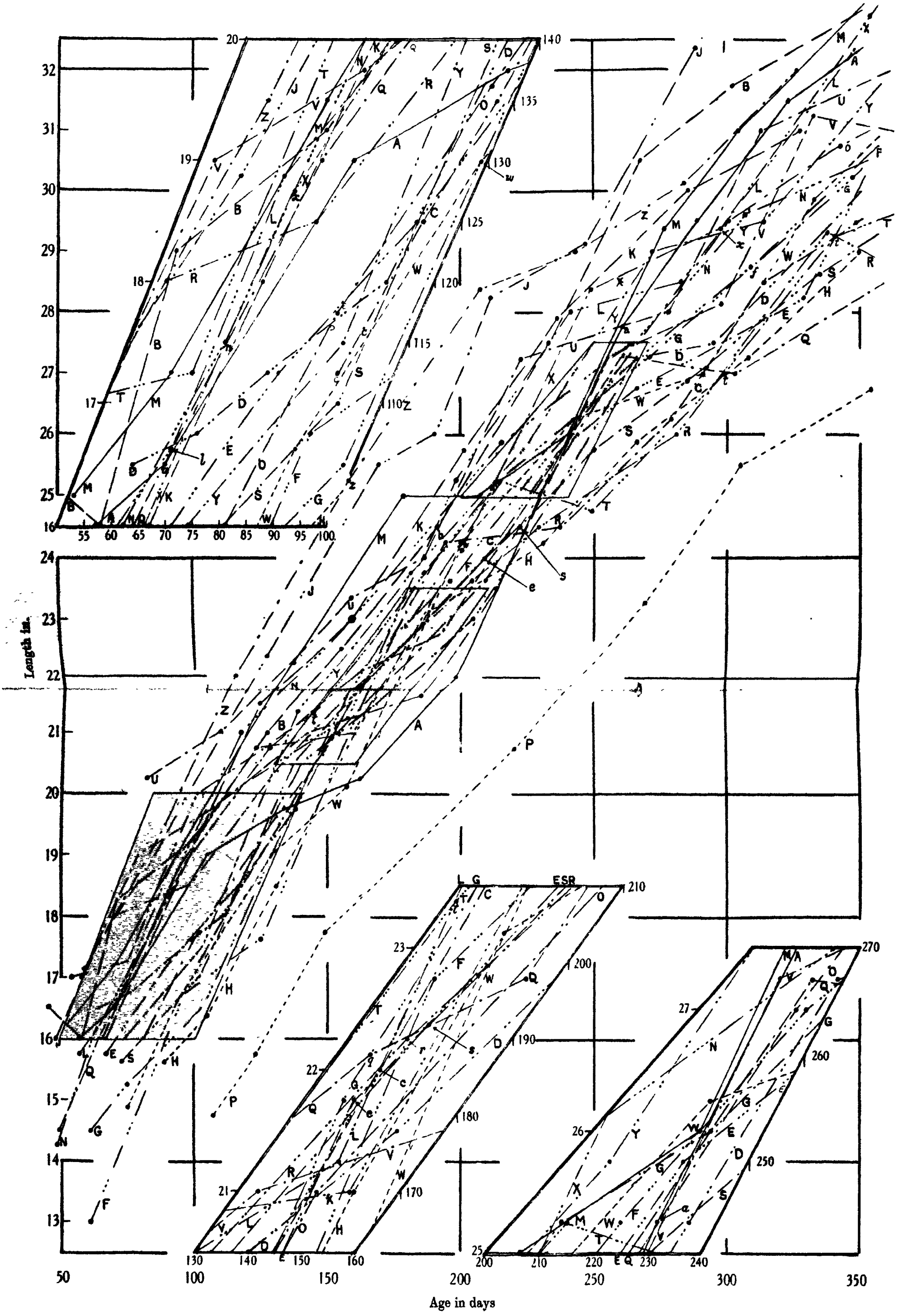

Length in.
Age in days
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
50
100
150
200
250
300
350
55
60
65
70
75
80
85
90
95
100
110
115
120
125
130
135
140
170
180
190
200
210
250
260
270

Fig. 4

by the variation in the times of fasting; in individuality of the pig in this regard, in bladder contents, in age at a definite weight and in weight for a definite fasting period, as this had occasionally to be varied to suit the convenience of the moment in the more important parts of the work. Finally the temperature of the environment was deliberately changed to study the effect of this on metabolism. The multiplicity of variables makes the data, numerous as they are, insufficient for more than a superficial study of this matter, when the necessarily rather large errors introduced by the circumstances above noted are taken into account. A few figures, however, will doubtless be of interest.

In 47 experiments in which the animals were between 70 and 150 lb. fasting live weight and in which the fasting period was 4 days compared as follows with 47 other experiments in which the weight limits were the same but the fasting period 5 days.

	Average weight loss in per cent. of live weight	
Period	Gross (incl. faeces)	Net (excl. faeces)
4 days	11·6	4·8 (35 results)
5 days	11·9	5·3 (27 results)

The effect of length of fast is slight but noticeable in the average figures, whether we take the gross or what for want of a better name we may call the net figures which were taken from a smaller number of results. (The quantity of urine is not considered, as the animals received water freely during the fasts, hence variations in this matter go in with the live-weight variations.)

That the percentage weight loss is also dependent on the actual live weight of the pig is clear from the following figures taken from 5-day fasts:

	Average weight loss in per cent. of live weight	
Fasting live weight	Gross (incl. faeces)	Net (excl. faeces)
70–150 lb.	11·9 (47 results)	5·3 (27 results)
300–380 lb.	6·5 (16 results)	3·2 (15 results)

All these results are quite in keeping with what, on theoretical grounds, might be expected.

The earlier set of figures need no comment in this regard. That the faeces passed should on an average be a less percentage of live weight in fasting for a definite period in the case of a larger animal is reasonable in view of the smaller proportion that the intestines make of the whole (6), and that the net percentage loss should also be less in the larger animal follows from the surface law.

HEALTH OF THE PIGS.

Finally a note must be added as regards the general health of the pigs. The pig P has already been mentioned as having developed rickets, and a consideration of Fig. 3 shows that as far as the relation between age and length is concerned this was an exceptional pig from the start. Pig K died suddenly from a complaint diagnosed as something analogous to black leg in cattle. Pig Q went into a decline while out at grass and was eventually shot, the nature of the complaint not being exactly determined. The rest of the animals remained quite healthy except for an attack of swine erysipelas which broke out in August, 1932, and for which both those affected and those apparently unaffected were treated by injection. The writer is indebted to Col. W. A. Wood, C.B.E., M.A., M.R.C.V.S., for the care of the health of the pigs throughout the work and also to the staff of the Calorimetry Department, more especially to Messrs K. C. Williamson, G. A. Childs and G. J. Hedge for assistance in the work generally.

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REPLY TO NOTE BY E. J. SHEEHY ON METHODS OF EXPERIMENTATION IN ANIMAL NUTRITION.

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(With Four Text-figures.)

The note by E. J. Sheehy on a method of correction in the weight curve of certain animals in group-feeding experiments (1) has been brought to the author's notice.

After perusal of the note the author is unable to discover any relevant facts which necessitate a modification of the method suggested by him and still considers that the correction put forward by Sheehy is based on false reasoning and is consequently inaccurate.

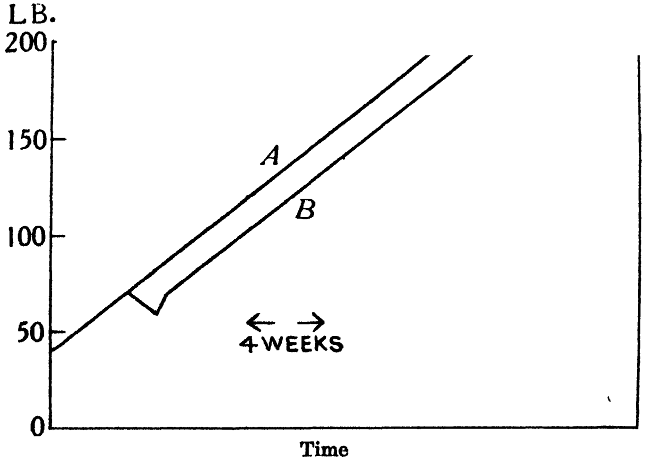

Fig. 1. If the rate of live-weight increase in animals was constant, then both Sheehy's and the author's method of correction would be applicable.

It is obvious that if swine made the same weekly gain while they were on experiment for studies of live-weight increase (say 8 lb. each week from weaning till bacon weight), the correction as suggested by Sheehy would be applicable (as would also be that suggested by us) (Fig. 1). Brody (2), among others, however, has shown that during the phase of growth preceding puberty the gain in weight is related to the growth already made. Indeed, Sheehy concedes this when he states that a 40 lb. pig adds 6 lb. to its weight in one week while a 200 lb. pig makes a gain of 12 lb. during the same period. It is clear, therefore, that if the normal live-weight increase of an experimental animal is temporarily checked, then on the resumption of normal growth its potential live-weight increase compared with that of identical animals, receiving no set-back, must be less over any period of time in which the weekly gains of the animals continue to increase; nor is adequate compensation made by adding to the final weight of the animal experiencing the disturbance an amount representing the difference between the weight of the normal animal and the weight of the other animal after normal growth was resumed. This point is illustrated in Fig. 2. Animal B receives a set-back when 60 lb. and resumes normal growth 2 weeks later at the same live weight. Thus if the point *b* (where the animal recovers) coincides with the point *a*, the two curves can be superimposed. From the construction of the curve: $x=199$, $y=173$, $cb=12$.

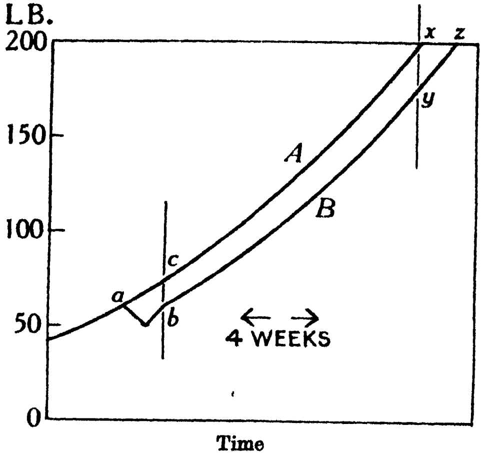

Fig. 2. Constructed on following basis: live weight of animal 40–80 lb., weekly gain 6 lb.; live weight 80–120 lb., gain 8 lb.; live weight 120–160 lb., gain 10 lb.; live weight 160–200 lb., gain 13 lb. Animal B receives a set-back equivalent to 2 weeks' loss of live-weight increase (*cb*). But *cb* (12 lb.) is not equal to *xy* (26 lb.).

Sheehy's correction involves the addition of 12 lb. to the live weight of animal B at *y* (173 lb.), which is 185 lb. The "corrected" live weight, however, is still 14 lb. less than that of the identical animal A whose weight is 199 lb.

Furthermore it can be shown that, if the period of disturbance of normal growth is prolonged, the correction suggested by Sheehy leads to greater differences. This is apparent when Fig. 2 is compared with Fig. 3 in which equilibrium in animal B is only regained after 4 weeks.

In this case again $x=199$, $y=150$, $cb=26$.

"Corrected" live weight of animal $B=150+26=176$, which in this case is 23 lb. less than the final live weight of the identical animal A.

The curves also show that if animal B remains on experiment for (i) 2 weeks in the first case and (ii) 4 weeks in the second case longer than animal A, the "final" live weights of the two animals are the same. This forms the basis of the method of correction suggested by the author.

Further obvious criticisms may be made of the data in Fig. 1 of Sheehy's note.

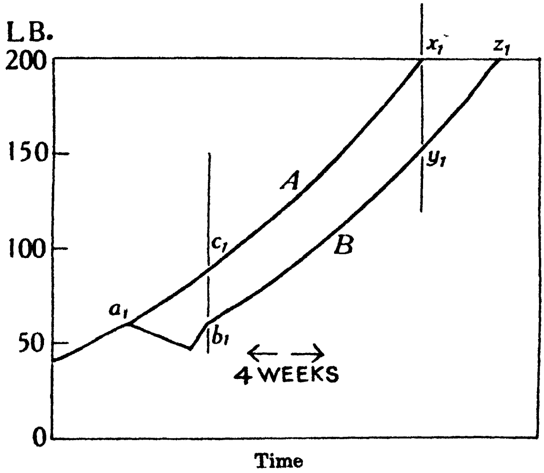

Fig. 3. Constructed as Fig. 2. Animal B receives a set-back equivalent to 4 weeks' loss of live-weight increase (c_1b_1). In this case the difference between c_1b_1 (26 lb.) and x_1y_1 (49 lb.) is greater than in Fig. 2.

(1) His correction is based on one single pig and an identical pig (actual or hypothetical). The method of correction suggested by the author was based on the results of a study of the life-history of 808 pigs.

(2) If the curves as he has drawn them are parallel, then the animals are not identical (Fig. 4).

(3) He assumes that the animal B experiences a set-back, makes an enhanced live-weight gain, and recovers normal growth again within one week. The curves are thus drawn too close to each other for carrying out a sufficiently accurate quantitative measurement to prove the issue one way or the other.

(4) From the course taken by the lower curve in his figure he appears to believe that live-weight increase is proportional to age. Brody (2) has shown that gain in weight up till the time of puberty is related to live weight or the growth already made. The author has also shown (1) that no correlation appears to exist between rate of live-weight increase and age.

In his criticism of the assumed live-weight gains of animals weighing 40 and 200 lb. respectively, he puts forward other figures for which he neither states the breed nor gives references as to their origin. The figures put forward by us were merely submitted as approximations (as we stated) to illustrate an argument. However, in this note the data on which the curves are based approximate Sheehy's own figures which suit our purpose equally as well.

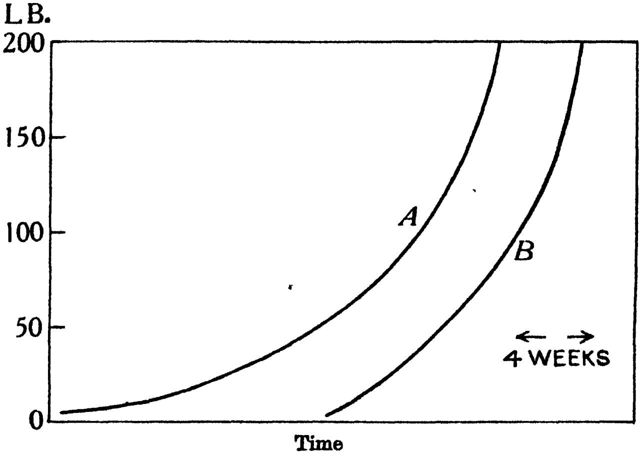

Fig. 4. These weight curves have been drawn parallel in so far as they have the same centre. Animal B, however, increases in live weight at a faster rate throughout.

We agree with the statement "if therefore the disturbance occurred in the fourth week Dunlop's compensation would be similar to that made if the interruption in live-weight increase occurred in the 13th week." Should an animal receive a set-back which is equivalent to the loss of 10 or 20 days live-weight increase at the time of the disturbance, then the compensation is similar no matter whether the interruption occurred in the 4th or the 18th week: the animal must remain on experiment for an extra 10 or 20 days as the case may be.

In the example given in our paper to illustrate the fallacy of Sheehy's correction, when we "assumed that the weight of animal A remained stationary for a fortnight," any enhanced live-weight gain had been corrected for and the set-back instanced was equivalent to the loss of a fortnight's live-weight increase of a 40 lb. animal. "The enhanced live-weight gain which occurs immediately after a suspension of progress" was demonstrated and appropriately corrected for later in the text (p. 606).

On these grounds the writer is unable to agree that the correction suggested by him is "much further from the truth than that adopted by Sheehy and Senior."

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VOLUME XXIV JULY, 1934 PART 3

THE CLOSE-GRAZING SCHEME OF PASTURE MANAGEMENT.

THE INFLUENCE OF SUCCESSIVE APPLICATIONS OF NITROGEN ON THE COMPOSITION AND YIELD OF THE HERBAGE.

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THE close-grazing or rotational system of pasture management has received wide attention in recent years, not only from the agricultural chemist but in one or other of its various modifications from the farmer and dairyman. Its underlying principles have been found to be sound and its main features capable of practical application. Given a fertile soil, suitable fertilisation and favourable seasonal conditions, it serves to furnish a highly digestible, high-protein herbage throughout the season.

The first investigatory work in Canada on this scheme was instituted by the Division of Chemistry of the Experimental Farm System at Ottawa in the spring of 1927. Four plots were laid out on a thick, uniform sward resting on a clay loam, the chief grass being meadow foxtail (*Alopecurus pratensis*). No fertiliser was applied until the autumn of the first season, when a top dressing of ammonium sulphate 50 lb., superphosphate 350 lb., muriate of potash 100 lb. per acre, was given. From 1928 to 1932, inclusive, the annual application has been nitrate of soda 160 lb., superphosphate 350 lb., and muriate of potash, 100 lb. per acre. The fertiliser was applied uniformly over the whole area comprising the four plots.

To simulate rotational and close-grazing, these four plots were cut by lawn mower as follows: A, weekly, B, fortnightly, and C, every third week. Plot D was cut by scythe for hay at the stage of "seed formed" with such aftermath as the season permitted. Each cutting was immediately weighed, sampled and its dry matter determined, the remainder being rapidly air-dried and ground for analysis. The results of this five-year period have appeared in detail in several papers[1], but the main conclusion is that the close-grazing scheme is one furnishing throughout the season, provided there is a sufficient and well distributed rainfall, pasturage rich in protein of a highly digestible nature. The dry matter of the herbage is really a high protein concentrate. Further, this scheme of pasture management is the best so far devised for producing the maximum amount of digestible protein per unit area.

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[1] "The protein content of grass, chiefly meadow foxtail (*Alopecurus pratensis*) as influenced by frequency of cutting," *J. Agric. Sci.* (July, 1929), **18**, Pt. 3; (January, 1930), **20**, Pt. 1; (July, 1931), **22**, Pt. 3. "A contribution from chemistry to the close-grazing system of pasturage," *Trans. of the Roy. Soc. of Canada* (1932), 3rd Series, **26**, Section 3, etc.

SEASON OF 1932.

The foregoing outline of the first Canadian experiment in close-grazing has been given for the reason that the same area has been used during the past two seasons in the endeavour to learn to what extent repeated doses of nitrogen might affect the yield and composition of the grass—a matter of economic importance in the management of grasslands under this scheme. The four adjacent plots *A*, *B*, *C* and *D* in the original layout were parallelograms with their long axis north and south. In the new arrangement of 1932 the plots, now numbered 25, 26, 27 and 28, were arranged crosswise of the old plots, *i.e.* with their long axis east and west. Each of these new plots, therefore, consists of one-quarter of each of the old plots, thus making them—the new plots—identical in respect to previous fertilising and cutting and therefore strictly comparable.

Fertiliser applications. The applications of nitro-chalk (15 per cent. nitrogen) during the season 1932 were as follows:

Table I. *Fertiliser* (*Nitro-chalk*). *Dates and rate per acre of application.*

Plot	First application 5. v. 32 lb.	Second application 10. vi. 32 lb.	Third application 22. vii. 32 lb.	Fourth application 23. viii. 32 lb.
25	160	—	—	—
26	160	160	—	—
27	160	160	160	—
28	160	160	160	—

The four plots throughout the season were cut on the same date, when the grass had reached a growth of approximately 7 in. Each cutting was weighed, thoroughly mixed, sampled and subsequently analysed as to dry matter and protein.

Dry matter. Table II presents the data for the dry-matter content and yields of the several cuttings from the four plots.

These data do not indicate any direct relationship between percentage of dry matter and days of growth or number of nitrogen applications. The

Table II. *Dry-matter content and yields per acre.*

Date of cutting 1932	Precipitation in.	Plot 25 Nitrogen, one application		Plot 26 Nitrogen, two applications		Plot 27 Nitrogen, three applications		Plot 28 Nitrogen, four applications	
		%	Yield lb.	%	Yield lb.	%	Yield lb.	%	Yield lb.
13. v	0·20	22·61	458	21·43	450	21·79	486	21·50	544
25. v	0·39	25·93	581	23·57	552	24·64	540	27·58	553
6. vi	1·64	24·20	454	22·45	479	22·86	482	25·15	500
27. vi	1·31	23·78	216	23·50	311	23·01	283	26·04	278
18. vii	2·11	25·91	175	25·66	308	25·22	251	27·12	290
5. viii	2·26	26·75	125	26·43	144	25·18	279	26·68	230
22. viii	1·91	26·07	193	22·66	168	23·54	329	21·92	215
7. ix	3·11	21·87	183	21·43	173	23·56	201	22·52	399
3. x	2·22	22·47	266	24·78	286	25·52	369	25·29	460
Total	15·15		2651		2871		3220		3469

averages from the nine cuttings for the dry-matter content for the four plots are 24·40, 23·54, 23·92 and 24·86—showing differences which might be accounted for by experimental error. The differences in the dry-matter content of the herbage from cutting to cutting are undoubtedly due in some degree to the proportion of clover present; it having been established that clover tends to have a lower dry-matter content than grass.

Yields of dry matter from any one plot fluctuate from cutting to cutting, due principally to seasonal conditions (chiefly rainfall).

Successive applications of nitrogenous fertiliser have markedly increased total yields of dry matter. The seasonal yields for the four plots, beginning with one application, are 2651, 2871, 3220 and 3519 lb. per acre. Two applications gave 220 lb., three, 569 lb., and four, 868 lb. per acre, more than one application.

Protein. The content and yield per acre of protein are set forth in Table III.

Table III. *Protein content and yields per acre.*

Date of cutting 1932	Precipitation in.	Plot 25 Nitrogen, one application		Plot 26 Nitrogen, two applications		Plot 27 Nitrogen, three applications		Plot 28 Nitrogen, four applications	
		%	Yield lb.	%	Yield lb.	%	Yield lb.	%	Yield lb.
13. v	0·20	30·07	137·7	30·56	137·5	29·75	144·5	29·94	162·5
25. v	0·39	22·82	132·6	22·41	123·7	22·77	122·9	24·18	133·7
6. vi	1·64	20·62	93·6	20·73	99·3	20·15	97·1	20·64	103·2
27. vi	1·31	19·38	41·9	23·06	71·7	22·75	64·4	21·16	58·8
18. vii	2·11	20·63	36·1	21·45	67·6	20·13	50·4	20·26	58·8
5. viii	2·26	20·53	25·7	20·58	29·6	23·86	66·6	23·06	53·0
22. viii	1·91	21·88	42·3	21·92	36·8	22·80	75·0	23·50	62·3
7. ix	3·11	24·35	44·6	24·31	42·1	22·85	45·9	24·97	99·6
3. x	2·22	22·46	39·7	20·81	39·7	19·00	70·1	19·89	91·5
Total	15·15		594·2		648·0		736·9		823·4

The first three cuttings on all four plots were made between the first and second applications of fertiliser. It will be observed that there is a rapid decline in the protein content, on all four plots, during this period—May 5th–June 6th—practically from 30 to 20 per cent. (dry-matter basis). These results furnish some evidence (1) of the ready and practically immediate availability of the nitrogen supplied and of its rapid assimilation by the herbage, resulting in a higher protein content, and (2) of the more or less quick decline in protein content, presumably as the supply of nitrogen becomes exhausted. Data of midsummer cuttings lend considerable support to these conclusions; but, owing to the spread of clover, especially on plots 25 and 26, from August to the close of the season, this effect of nitrogen is not observable in the results from the latter cuttings. Average percentages of protein of the herbage of the four plots, for the first seven cuttings, *i.e.* until August 22nd, are 22·27, 22·97, 23·17 and 23·27; those for the entire season are 22·53, 22·87, 22·67 and 23·07. Under the conditions of this experiment it would seem that the nutritive value of the herbage, as measured by protein content, has not been materially influenced by additional applications of nitrogenous fertiliser.

Additional nitrogen has resulted in increased yields of protein, the seasonal weights for this constituent for the four plots being 614, 668, 737 and 823 lb. per acre respectively. The increases in protein yield per application of 160 lb. nitro-chalk for plots 26, 27 and 28 are 54, 69 and 86 lb. per acre. Considering recovery of nitrogen in terms of protein every pound of additional nitrogen has given, from plot 26, 2·16 lb. protein, from 27, 2·76 lb. and from 28, 3·44 lb.

To present in summarised form the influence of successive applications of nitrogen on dry-matter and protein yields, Table IV has been constructed.

Table IV. *Influence of successive applications of nitrogen on yields of dry matter and protein (lb. per acre).*

Precipitation in.	Date of application 1932	Plots fertilised	Dry matter (lb.)				Protein (lb.)			
			Plot 25	Plot 26	Plot 27	Plot 28	Plot 25	Plot 26	Plot 27	Plot 28
2·18	5. v	25, 26, 27, 28	1493	1481	1508	1597	364	361	365	399
3·47	10. vi	26, 27, 28	391*	619	534	568	78*	139	115	118
4·17	22. vii	27, 28	318*	312*	608	495	68*	66*	142	115
5·33	23. viii	28	449*	459*	570*	859	104*	102*	116*	191
		Totals	2651	2871	3220	3519	614	668	738	823

* No application of fertiliser.

In this table (IV) the yields are given for the intervals between the several applications of nitrogenous fertiliser and thus the influence of these successive applications of nitrogen is clearly brought out. Thus, between plots 25 and 26, receiving one and two applications, respectively, there is a marked increase in both dry matter and protein from plot 26 following the second dressing of fertiliser. Similarly, on plots 27 and 28, increases follow the third application, and on plot 28 from the fourth application. In a word, with each additional dressing of nitrogen there has been a marked response in increased yields of both dry matter and protein.

SEASON OF 1933.

Fertiliser application. The applications of nitro-chalk (15 per cent. nitrogen) during the season of 1933 were as follows:

Table V. *Fertiliser (nitro-chalk). Dates and rate of application per acre.*

Plot	First application 26. iv. 33 lb.	Second application 5. vi. 33 lb.	Third application 22. vii. 33 lb.	Fourth application 23. viii. 33 lb.
25	160	—	—	—
26	160	160	—	—
27	160	160	160	—
28	160	160	160	160

As in the previous season, the cutting of the four plots was made throughout the season on the same day, the growth having reached a height of, approximately, 7 in. The procedure as to mixing, sampling, weighing and analysis of 1932 was also followed.

Dry matter. The data for the dry-matter content and yields of the several cuttings from the four plots are presented in Table VI.

Table VI. *Dry-matter content and yields per acre.*

Date of cutting 1933	Precipitation in.	Plot 25 Nitrogen, one application %	Yield lb.	Plot 26 Nitrogen, two applications %	Yield lb.	Plot 27 Nitrogen, three applications %	Yield lb.	Plot 28 Nitrogen, four applications %	Yield lb.
18. v	**2·35**	**21·68**	**545**	**21·39**	**756**	**21·61**	**600**	**23·18**	**804**
1. vi	**1·17**	**20·93**	**759**	**20·04**	**885**	**20·58**	**743**	**22·09**	**774**
16. vi	**0·53**	**22·91**	**138**	**26·55**	**215**	**24·68**	**174**	**26·34**	**137**
11. vii	**3·27**	**26·01**	**199**	**27·22**	**276**	**26·33**	**268**	**28·86**	**208**
17. viii	**2·38**	**34·17**	**357**	**36·28**	**295**	**36·35**	**389**	**36·38**	**250**
7. ix	**2·53**	**22·42**	**266**	**24·47**	**291**	**26·74**	**456**	**21·81**	**480**
10. x	**1·83**	**27·60**	**159**	**28·82**	**166**	**29·61**	**222**	**29·12**	**331**
Total	**14·06**		**2423**		**2884**		**2852**		**2984**

The dry-matter content (percentage) appears to be influenced, chiefly, by two factors—period (or days) of growth and the amount of rainfall immediately preceding and during that period. The percentage of dry matter increases with growth, but an abundance of available soil moisture under favourable temperatures tends to offset this effect and is undoubtedly the more important factor of the two. Dry weather during a long period between cuttings, as might be expected, resulted in a herbage with a high dry-matter content.

The averages from the seven cuttings for the dry-matter content for the four plots are 25·10, 26·39, 26·54 and 26·82 per cent. Though a tendency to increase in dry-matter content is to be observed, the increases are slight and could, no doubt, be accounted for otherwise than by the successive applications of nitrogenous fertiliser.

The influence of successive applications of nitrogen on the dry-matter yields is notable, though the data for plot 27 are not in line. This plot appeared to suffer most from winter killing and, in consequence, the yields from the first three cuttings were decidedly lower than those from plots 26 and 28. It made a recovery towards the middle of July, but the low early cuttings bring down its total for the season. The increases over that from one application are: 461 lb. from two, 429 lb. from three (plot 27) and 561 lb. from four applications.

Protein. The data for protein content and yields per acre for the season are presented in Table VII.

Table VII. *Protein content and yields per acre.*

Date of cutting 1933	Precipitation in.	Plot 25 Nitrogen, one application		Plot 26 Nitrogen, two applications		Plot 27 Nitrogen, three applications		Plot 28 Nitrogen, four applications	
		%	Yield lb.	%	Yield lb.	%	Yield lb.	%	Yield lb.
19. v	2·35	22·16	121·0	23·31	176·0	22·09	133·5	20·94	168·0
1. vi	1·17	18·62	141·0	19·32	171·0	18·62	138·0	17·29	134·0
16. vi	0·53	16·85	23·3	17·54	37·7	21·30	37·0	21·99	30·0
11. vii	3·27	18·52	37·0	19·46	53·7	20·15	54·0	19·55	40·7
17. viii	2·38	16·95	60·4	17·28	51·0	18·19	70·7	19·33	48·3
7. ix.	2·53	24·80	66·0	23·06	67·0	22·00	100·0	26·64	128·0
10. x	1·83	22·21	35·3	19·83	32·0	21·11	46·0	22·11	73·2
Total	14·06		484·0		588·4		579·2		622·2

Considering first the protein content, it will be observed that there are fluctuations from cutting to cutting in the herbage from all four plots. These most probably are chiefly to be attributed to changes in the character of the herbage, for observational notes during the season show an increase in the growth of weeds (chiefly dandelion) at one period and of clover at another. The former would lower the percentage of protein, the latter would raise it.

The average percentages of protein (dry-matter basis) of the herbage of the four plots for the season are 20·02, 19·97, 20·49 and 21·12. In the light of what has been said in regard to changes in the character of the herbage, these data, as those of the previous season, afford no evidence that the nutritive qualities of the grass, as measured by protein content, has been materially affected by the successive applications of nitrogen.

Increased yields of protein from additional applications of nitrogen, however, have been obtained, though the season's yield from plot 27, for the reason already stated, is not, as might otherwise be expected, intermediate between those of plots 26 and 28.

Influence of rainfall. The factor of paramount importance influencing yield of both dry matter and protein is the amount of soil moisture available for root absorption. It follows therefore that the rainfall—amount and distribution—during the period of growth, *i.e.* between grazings (or cuttings) will not only markedly affect results but may indeed determine the degree of success of this system of pasturage. To illustrate this influence, two periods—one of abundant and one of sparse rainfall—may be cited from the latter of the seasons of this investigation.

Table VIII. *Influence of rainfall on yield.*

Rainfall in.	Days of growth	Period of growth 1933	Yields per acre: Dry matter lb.	Yields per acre: Protein lb.
1·17*	13	18. v–1. vi	759	141·0
0·53	16	1–16. vi	138	23·3

* Plus 2·35 in. May 1st–18th.

To present in briefest form the main results from this enquiry, the subjoined table (IX) has been prepared. It shows at a glance that marked increases in the yields of both dry matter and protein have been

Table IX. *Dry matter and protein. Yield per acre from successive applications of nitrogenous fertiliser.*

	Dry matter applications				Protein applications			
Year	One	Two	Three	Four	One	Two	Three	Four
1932	2651	2871	3220	3519	614	668	737	823
1933	2423	2884	2852	2984	484	588	579	622
Total	**5074**	**5755**	**6072**	**6503**	**1098**	**1256**	**1316**	**1445**

obtained from successive dressings of nitrogenous fertiliser applied throughout the growing season.

This work, in addition to showing the marked influence of nitrogen in increasing the yields of dry matter and protein, has confirmed previous results in respect to the high protein character of young grass. While some evidence was obtained in the spring of 1932 that applications of nitrogen increased the protein content of the herbage, later changes in the proportion of legumes to grasses rendered it impossible to assess rightly the influence of the fertiliser upon percentage of protein. It has also indicated that an ample and well-distributed rainfall is a most important factor, practically, a *sine qua non*, towards the successful operation of the close-grazing scheme of pasture management.

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THE RÔLE OF FIELD DRAINS IN REMOVING EXCESS WATER FROM THE SOIL.

I. SOME OBSERVATIONS ON RATES OF FLOW FROM OUTFALLS.

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(With Three Text-figures.)

The history of field-drainage practice reveals many variations in the methods employed. The one feature which they have in common is the provision of graded and unobstructed channels to accelerate the flow of surplus water from the soil to the outfalls. With the exception of surface drains, all methods of field draining are inevitably accompanied by considerable disturbance and opening up of the soil and subsoil along definite lines and to varying depths, during the laying of the drains or the formation of the channels. In all other respects such as depth, distance, shape of channel, type of pipes or lining to the channel, and methods of laying, practice varies considerably. In the course of the development of present-day systems, the older large and roughly made stone drains gradually gave way to cylindrical unglazed tiles, while the shallow hand-made plug drains of a hundred years ago were followed by mechanically drawn mole drains. At the present time efforts are being made to combine both methods in a single operation. There are actually in existence a number of machines which (1) draw a mole channel and line it with tiles, or (2) manufacture a continuous porous pipe *in situ* behind a moving mole plough, or (3) fill the mole channel with coarse gravel as it is made. The aim of all is to produce an efficient channel and to give it durability.

OUTFALL RECORDS OF TILE-DRAIN SYSTEMS.

From the nature of the problems involved, field drainage does not lend itself readily to direct and precise experiments. Much is to be learned, however, by the observation of actual working drains in the field. Unfortunately, records of such observations are not plentiful. About the middle of last century numerous papers on field-draining practice and problems appeared in the *Journal of the Royal Agricultural Society of England*. Among them is one by J. Bailey Denton (1), containing the tabulated records of rainfall, outfall, level of the water table, barometric pressure, soil temperature, and air temperature, over a period from October 1856 to May 1857, on a new field-drainage system laid down by him on the Hinxworth Estate in Hertfordshire. His outfalls covered a range of soil types, of which the lightest and heaviest are discussed here. The character of the soils and the method of draining them can be summarised as follows:

Soil parent material ...	Gravel drift on lower chalk	Gault clay
Analysis by J. T. Way	Sands and clays, 24·4 % Carbonate of lime, 68·3 %	Clay, 63·3 % Carbonate of lime 32·4 %
Condition of land ...	Lay very wet before draining	Very stiff and impenetrable
Type of drains	Wide parallel, 4 ft. 4 in. to 4 ft. 11 in. deep, 57 yd. to 59 yd. apart	Close parallel, 4 ft. deep, 25 ft. apart

The records constitute a detailed account of events during the whole drainage season, of which the main features have been summarised in an earlier paper (2). Bailey Denton reviewed his figures on a monthly basis and drew attention to the gradually increasing clearance of excess water as the winter advanced. On this view he found that more water was cleared from the light land than had fallen on it as rain in the months December and February, and that this was the case on all the recorded fields in February. The writer has examined the figures on a different basis. When the rainfall and outfall records for the year are plotted, it is seen that alternations of wet and rainless periods are accompanied by

Table I. *Wet periods and resultant outfall as shown by J. Bailey Denton's records.*

	Rainfall		Light-land outfall		Heavy-land outfall	
Period	In.	Gals. per acre	Gals. per acre	As % of rainfall	Gals. per acre	As % of rainfall
Oct. 6th–31st	1·34	29,660	12,800	43·2	0	0
Nov. 1st–25th	1·07	23,970	7,630	31·8	0	0
Nov. 26th–Dec. 4th	0·56	12,540	7,600	60·6	520	4·1
Dec. 5th–29th	1·62	36,290	25,590	70·5	5,230	20·4
Dec. 30th–Jan. 8th	0·54	12,100	7,900	65·3	3,950	32·6
Jan. 9th–20th	1·18	26,520	19,070	71·8	15,520	58·6
Jan. 21st–Feb. 5th	0·77	17,230	23,840	138·3	14,120	81·9
Feb. 6th–28th	0·18	3,970	22,120	557·9	7,820	197·2
Mar. 1st–31st	0·82	18,550	*8,420	45·5	3,310	17·8
April 1st–30th	1·44	32,570	6,700	20·6	6,180	19·1
May 1st–31st	0·75	16,970	4,180	24·7	3,420	20·0

* At this date a new field was substituted in the records.

marked flow and ebb in the rates of outfall. Table I presents the data in periods of which each begins with the onset of one flow and ends with the onset of the next, *i.e.* during the more active part of the drainage season; the months March, April and May, unaccompanied by marked variations in outfall, are left as such. The results are presented graphically in Fig. 1

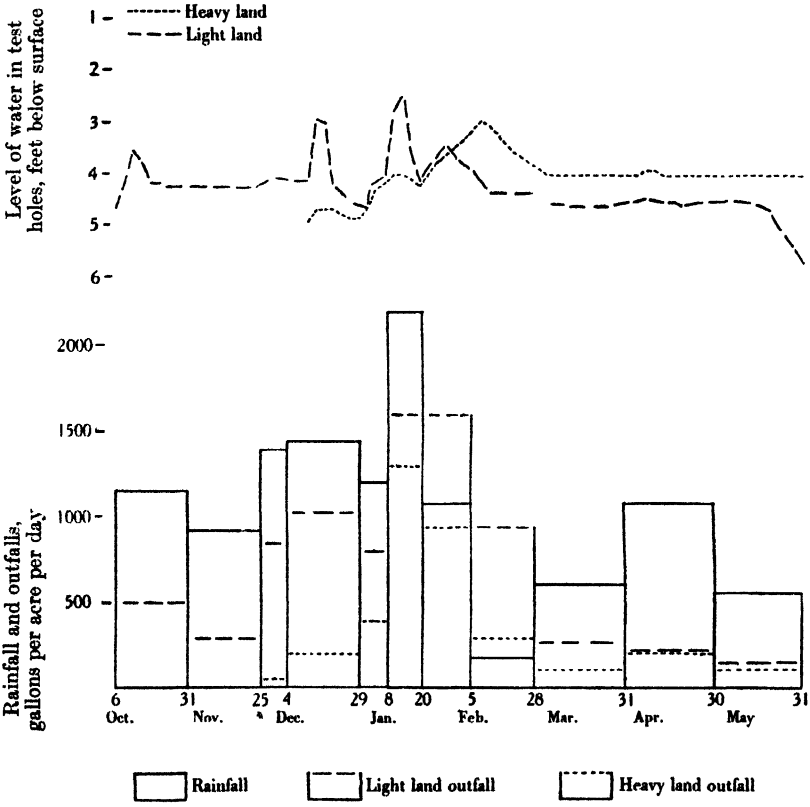

Fig. 1. J. Bailey Denton's drainage records—Hinxworth, 1856–7.

in conjunction with the movements of the water table on the two fields, as assessed by daily measurements in test holes dug between the drains.

From Table I it can be seen that the soil became gradually less able, as the winter advanced, to absorb or hold all the rain which fell on it, and a steadily increasing proportion of each fall apparently ran off via the drains. The figures for the heavy land in this respect are much more regular than those for the light land. As one flow followed another the drains became less able to clear the excess before the next flush occurred, until during the periods January 20th–February 5th, and February 5th–28th, the light-land drains ran off more water than fell on them as rain, the heavy-land drains showing a similar but less marked tendency. By the beginning of March the position had substantially improved, a dry February having enabled the drains to deal with the accumulated excess and the soil to absorb more of the rain which fell on it. It must be remembered that the light land lay wet before draining and that it very probably received water from neighbouring higher ground, so that the rainfall cannot be safely regarded as solely responsible for all the water with which the drains were called upon to deal.

WATER TABLE MOVEMENTS.

An examination of the data respecting run-off in conjunction with movements of the water table reveals some interesting points. It must be noted that the light-land drains ran continuously from October 1st, while the heavy-land drains did not commence until November 27th. Bailey Denton dug his test holes midway between drains and about 2 ft. deeper. On the light land, the drains in early October were running, despite the fact that the water table apparently was 1 ft. below them. A week later it had risen to the same level and shortly afterwards to 9 in. above them, causing a marked increase in the outfall rate. From Fig. 1 it is apparent that the onset of each flush of the light-land outfall is associated with a marked though temporary rise in the level of the water table and a subsequent fall to about drain level. Occasionally this was followed by a period of stability until the next wet spell. This was not the case, however, during January, when several wet spells followed one another quickly, causing further upward movements of the water table before it had time to subside to normal, and involving the presence of a surplus of water in the soil to be cleared later when the next rainless period occurred. Such a rise began on January 20th, and stability was not attained again until February 12th, a week after the beginning of the next period, February 5th–28th. The outfall rate increased from January 20th and again from February 6th, and it is noteworthy that it fell ultimately by February 12th to the rate recorded for February 6th.

The test holes on the heavy land told a different story. Except during a few days in early October, the water did not appear in them until November 27th, when 0·54 in. of rain caused the water to stand in them at a depth of 4 ft. 11 in. (for two days only). The drains—at a depth of 4 ft.—ran slowly. After December 9th, each wet spell caused a marked rise of the water level in the test holes, but no marked fall took place until

February and even so there was no sign of stability until March 2nd, from which date the level was approximately the same as that of the drains. Meanwhile the peak was attained on February 9th at a depth of 2 ft. 11 in. The fluctuations in outfall rates, however, were frequent and considerable, and one is driven to the conclusion that there is no connection between the apparent level of the water table and the performance of the drains. Although these were only 25 ft. apart, as contrasted with 59 yd. on the light land, and although the level of water in the test holes was well below the level of the drains from December 12th until January 20th, and considerably above it between January 20th and March 1st, each spell of rain produced marked flushes from the outfall during both periods. On undrained heavy land the water table was first recorded at a depth of 3 ft. and proceeded to rise steadily a further 8 in. during the eight rainless days which followed, although it disappeared from the test holes on the drained land and the outfall rate steadily fell. Further, the heavy rain of December 13th (0·45 in.) produced a rise of 3 in. in the drained land test holes, and one of 2 ft. in that on the undrained land. From February 6th, the outfall rates on all fields steadily diminished, there being no further heavy falls of rain during the remainder of February and March. One or two wet days late in March, and a fall of 0·46 in. on April 5th, produced a minor flush, as also did 0·3 in. on April 13th followed by 0·15 in. on the following day, but from the latter date, all outfalls continued at low rates until the end of May. During March, April and early May the water-table readings continued remarkably steady, but from May 14th, on the light land, the level fell rapidly to a depth of 6 ft. 6 in. below the surface. These observations on the heavy land can be explained by surface run-off through the comparatively permeable top soil and the disturbed earth filling the drain trenches. While most of the surplus water, once the heavy land had absorbed moisture to its maximum capacity, could quickly reach the drains (even more quickly than on the light land), some would drain into test holes and, with successive falls during the winter, would slowly fill them up. On the undrained land, with no easier egress for the surplus, the test hole would function as a catchpit for the immediate neighbourhood and receive much larger amounts of water in each wet spell, so that the water level in it would rise correspondingly more quickly.

These records were the subject-matter of protracted discussion before the Institute of Civil Engineers (3). This body of opinion found it difficult to credit the run-off of about three-quarters of the rainfall during the winter as shown by the light-land outfall records, and no data were available to indicate to what extent the figures were influenced by inflow from neighbouring higher ground. In explaining his records Bailey Denton called attention to the very different behaviour of light and heavy soils and also to the variations in the activity of drainage systems consequent on the varying moistness of the preceding season, especially during the summer. He accepted the evidence of his heavy-land test holes as indicating water-table movements, and was confirmed in his opinion by one remarkable performance of his heavy-land drains soon after the water in the test holes rose to their level. This occurred after 0·54 in. of rain on January 20th, and the outfall record rose from 125 gals. per acre per day on January 19th to 5150 on the 20th. He contrasted this with the effect of 0·45 in. on December 13th, over a month earlier, when the water in the test hole rose from 4 ft. 9 in. to 4 ft. 8 in. and the outfall rate from 160 to 975 gals. per acre per day.

A considerable difference is to be expected in any case, as the land was steadily becoming more saturated; but it may not have been so great as was actually recorded, for as will be shown later, the rapid fluctuations of heavy-land outfalls necessarily involve an error in estimates dependent on daily readings. Bailey Denton's explanation of events was based on direct percolation, even through heavy soil, which he suggested absorbed the rain until it was saturated to the surface. The water was held by capillary forces, and subsequent additions at the surface displaced equal amounts below into the drains by simple hydrostatic pressure. Bailey Denton made his outfall measurements with a stop-watch and buckets graduated in pints. His critics considered this apparatus inadequate, but made no comment on the limitations of single daily readings. The method used to obtain the information submitted later in this paper was the same, except that the collecting vessels were chosen in accordance with the rate of flow. Daily readings have proved adequate to secure a good general idea of events in the working of field drains on various types of soil during a whole season, to measure the effects of a succession of wet and rainless periods, and to give an idea of the capabilities of individual drainage systems. The more marked fluctuations connected with heavy land, however, point obviously to the need for closer observations of outfall performances. The need for self-recording drain gauges has been realised for some time, but the difficulties of producing and erecting meters to suit field-drainage systems and to cope satisfactorily with tremendous fluctuations of flow have proved by no means easy of solution. The nature of the whole problem of drainage of necessity involves very little space between the outfall pipes and the ditch into which they empty. Promising apparatus has been devised both by H. Janert (4) and by J. H. Blackaby and others (5). Records obtained by the latter show the type of fluctuations which occur from hour to hour and the way in which the drains can respond to individual showers of rain. Blackaby's meter has been proved capable of dealing with flows up to 240 gals. per hour, a figure which in ordinary circumstances may be adequate but on areas of 5 acres, especially on heavy land, will not infrequently be exceeded (in the present investigation, an outfall, serving 4 acres of grassland, on one occasion was running at the rate of 3870 gals. per hour).

FACTORS INFLUENCING PERCOLATION.

The behaviour of outfalls is influenced by many factors, some of which are by no means obvious. W. B. Haines and B. A. Keen (6) comment on the problem in connection with their work on drawbar pull in cultivations on the Broadbalk field at Rothamsted. They record an instance in which they found that the drain-efflux rates were closely related to the heaviness of the soil, and surmised that the higher flow from the heavier plots at this particular moment was caused by the relative impermeability of those plots, resulting in more of the percolating water being sidetracked into the drain, instead of descending vertically into the subsoil. Keen (7), commenting on the same observations at a later date, suggested that the heavier plots have longer periods of outfall due to slower percolation, and that on this particular occasion the lighter plots were nearing the end of their run and were therefore showing lower outfall rates. Both of these factors are important. If the soil were at all impermeable the first factor suggested would be the more important. If the soil were fairly permeable, the latter explanation would be more satisfactory. Only close records of the whole period of flow could demonstrate the vital facts, as to whether a larger total amount of water ran out of the heavier plots and whether it ran, on the whole, more slowly or more quickly. Actual events on any particular occasion will reflect the result of a large number of variable factors of which now one, now another, will be the more potent. With general geological, physiographical and climatic conditions this account is not concerned. In the case of a particular parcel of ground it is the texture of the soil, as reflected by the size distribution of the mineral particles together with the amount of organic matter, which decides its general drainage properties. In normal circumstances, weathering results in the aggregation of these constituents into crumbs with the production of a definite soil structure. The structure of a soil is not uniform throughout its profile and is not immutable. Annual seasonal changes take place

Table II.

Outfall *Z*, serving 3·9 acres old grassland, fall 1 in 80.
B, serving 6·5 acres arable (summer fallowed), fall 1 in 120.
E, serving 5·2 acres arable (summer fallowed), fall 1 in 110.
M, serving approx. 15 acres arable (summer fallowed), fall 1 in 300.
Rate of flow—gallons per hour.

Date 1931	Rainfall in.	*Z*		*B*		*E*		*M*	
Oct. 29th	0·21	—		—		—		—	
Nov. 3rd	0·02	—		—		—		—	
4th	0·09	—		—		—		—	
5th	0	—		—		—		—	
6th	0·4	—		—		—		—	
7th	0·04	9.0 a.m.	0	—		—		—	
		10.0	50	—		—		—	
		2.0 p.m.	0	—		—		—	
8th	0	—		—		—		—	
9th	0·21	3.30 p.m.	0	0		0		0	
		4.20	55	—		—		—	
		4.50	333	—		—		—	
		5.5	246	—		—		—	
		5.25	176	—		—		—	
		5.45	162	—		—		—	
		6.15	98	0		0		0	
10th	0·12	—		—		—		—	
11th	0·13	2.15 p.m.	7·8	0		0		1.30 p.m.	18·6
		3.15	6·4	—		—		—	
		3.55	6·4	—		—		—	
12th	0	12.25 p.m.	24·1	1.0 p.m.	8	—		1.0 p.m.	41
		1.15	22·6	3.45	7·9	0		3.35	29
		3.15	17·8	—		—		—	
		4.0	16·9	—		—		—	
13th	0	8.55 a.m.	1·3	9.25 a.m.	4·3	0		9.15 a.m.	7
		4 30 p.m.	0	1.0 p.m.	4	—		12.50 p.m.	5
		—		4.10	3·5	—		4.0	4·4
16th	0	3.40 p.m.	0		1	0		3.50 p.m.	0·3
17th	0	10.30 a.m.	0		0 9	0		10.50 a.m.	0·2
18th	0·49	4.0 p.m.	0	0		0		—	
		8.45	1440	0		0		9.0 p.m.	184
		9.20	1090	—		—		9.55	243
		9.37	882	—		—		10.30	225
		10.5	729	—		—		—	
		10.55	709	—		—		—	
19th	0	8.45 a.m.	680	9.15 a.m.	60	9.30 a.m.	37	9.3 a.m.	486
		9.35	541	10.40	63	10.10	45	10.35	424
		10.5	479	11.45	69	10.50	57	11.40	361
		11.0	381	1.35 p.m.	75	11.25	58	1.45 p.m.	290
		11.20	364	2.55	75	12.0 noon	60	2.45	279
		12.5 p.m.	308	3.35	80	12.30 p.m.	66	3.50	236
		12.40	284	5.40	81	1.30	66	5.30	161
		2.13	225	6.35	74	2.5	70	6.25	187
		3.20	197	—		2.55	71	—	
		4.10	177	—		3.10	71	—	
		4.50	162	—		3.25	73	—	
		5.55	146	—		4.0	74	—	
		—		—		5.15	76	—	
		6.55	129	—		—		—	
		—		—		6.5	75	—	
		—		—		6.50	75	—	
20th	0	8.55 a.m.	61	9.25 a.m.	54	9.5 a.m.	52	9.20 a.m.	80
		10.0	64	2.30 p.m.	60	9.55	51	2.20 p.m.	73
		1.45 p.m.	54	—		3.0 p.m.	46	—	
21st	0	1.45 p.m.	0	1.20 p.m.	43	2.10 p.m.	16	2.0 p.m.	33
22nd	0	—		—		—		—	
23rd	0·11	—		—		—		—	
24th	0	2.25 p.m.	61	3.10 p.m.	57	2.50 p.m.	27	3.0 p.m.	67
25th	0·04	—		—		—		—	
26th	0·15	11.20 a.m.	31	12.15 p.m.	51	11.25 a.m.	37	12.0 noon	53
27th	0·30	9.0 a.m.	111	9.30 a.m.	138	9.5 a.m.	158	9.25 a.m.	230
		12.45 p.m.	94	1.30 p.m.	125	1.0 p.m.	148	1.25 p.m.	212
		5.25	3870	6.10	364	5.45	552	2.27	1120
		5.40	2800	—		—		—	
		6.25	1560	—		—		—	
28th	0	9.50 a.m.	508	—		10.5 a.m.	1070	10.55 a.m.	1810
		11.35	365	—		—		—	
29th	0	—		—		—		—	
30th	0	9.40 a.m.	50	10.25 a.m.	228	9.50 a.m.	231	10.15 a.m.	266

but even they display variations from one year to another. Different treatments have different effects, so that the recent agricultural history of any field has an important influence on its drainage properties at any given moment. In particular the permeability and water-absorbing power of the worked soil, and of the subsoil too, are considerably influenced by previous treatment. The total amount of rainfall for the season, the manner in which it is distributed over the season, and the intensity of individual falls of rain, all exert an effect on drainage results. With so many variants in operation, it is a difficult matter to trace the influence of any one.

THE BEHAVIOUR OF MOLE-DRAIN SYSTEMS ON HEAVY LAND.

Since 1930 observations have been in progress on the Cambridge University Farm in connection with mole-draining investigations, with the object of obtaining more accurate information on the performance of drains and the factors which influence them. The general nature of the work has already been described (2). All the observations were made on heavy gault clay soil, on drainage systems freshly laid in the ordinary course of farm management. Mole draining with steam tackle was the means adopted, with the channels 20–24 in. deep and 9–10 ft. apart, except on grassland, where sets of three were drawn in the bottom of each existing furrow. The mole systems were provided with collecting mains of tiles leading to piped outfalls. These were watched as closely as practicable, particularly after falls of rain, and measurements of the outfall rates were made by means of suitable collecting vessels and a stop-watch. Table II illustrates the method adopted and the nature of the variations in flow at the beginning of the drainage season 1931–2.

The field in which outfall *Z* was situated was mole drained towards the end of September 1931, and the areas serving *B*, *E* and *M* in the early months of the same year. October was a rainless month, but with November wet weather arrived. On November 7th, after 0·4 in. of rain during the preceding day, *Z* began to run at 9 a.m., rose to a rate of 50 gals. per hour and ceased by 2 p.m. No others ran. On November 9th, it began to rain in the morning, but no drains had commenced to run at 3.30 p.m. *Z* began soon after 4 p.m. and within 50 min. was running at 333 gals. per hour; by 6.15 p.m. this had fallen to 98. On the 10th and 11th other small flushes occurred. A fall of 0·49 in. on the 18th affected all drains to a marked degree, though the rates and their changes varied greatly. The rain ceased for a time at 7 p.m. and *Z* attained its maximum output 2 hours later. Further rain during the night brought *B* and *E* into action, their rates slowly increasing to a modest maximum during the following day. Within 3 days *Z* was dry again, but the others, on arable land, continued to run gently. A fall of 0·15 in. on the 26th, followed by 0·3 in. on the 27th, produced a marked response, *Z* on this occasion increasing to almost 4000 gals. per hour by 5 p.m., from 94 at 1 p.m. The arable land drains once more came into action later and more slowly, their rates increasing during the night. January, February and March, 1932, were comparatively rainless months with few single daily falls exceeding 0·1 in. There was, as a result, very little activity on the part of the drains. April and May, however, were extraordinarily wet with heavy individual falls of 0·2–0·5 in. within 24 hours, every few days. These were accompanied by frequent flushes from the drains with which it was impossible to keep pace owing to the high rates of flow, the frequency of the fluctuations and repeated inundation of the outfalls. On May 3rd *Z* was running at 4100 gals. per hour. This period of excessive rains ended on May 28th and from then until June 30th there was practically no rain. 1·2 in. of rain, spread over the last 3 days of the wet period, kept all the drains running strongly but within 4 days of its cessation those on the grassland were dry, while those on the arable land continued for a further 7 days. The June drought was ended by the incidence of 0·61 in. in the early hours of July 1st, but *Z* was the only outfall to show any measurable response. In about 1 hour of flow it rose from 0 to 70 gals. per hour and receded to 0 once more. On the arable land only one or two outfalls responded, and then only with a trickle of short duration.

COMPARISON OF BEHAVIOUR OF GRASS AND ARABLE LAND.

Considering the freshly moled grassland area served by *Z*, two points strike one immediately. The clearance of individual falls of rain took place quickly and the intensity of flow increased with successive falls of rain. The arable land cleared much more slowly and the run-off was much less intense. The outfall records for *Z* and *E* are summarised for comparison in Table III, giving outfall rates in gallons per hour, and are diagrammatically expressed in Fig. 2 as run-off in gallons per acre per hour.

Table III. *Summary of outfall records for grassland,* Z, *and arable land,* E, *at commencement of drainage season.*

	Date 1931	Rainfall in.	Fluctuation, *Z* gals. per hr.	Period of run *Z* (hr.)	Fluctuation, *E* gals. per hr.	Period of run *E* (hr.)
(1)	Nov. 7th	0·40	0–50–0	5	0	0
(2)	9th	0·21	0–333–98	6	0	0
(3)	18th	0·49	0–1440–8	57	0–75–15	60
(4)	27th	0·30	94–3870–50	75	148–1070–102	120

THE EFFECT OF THE DISTRIBUTION OF RAINFALL DURING THE SEASON.

The manner in which the response to individual falls of rain is determined by preceding events is well illustrated by these data. The condition of the soil on November 7th was obviously such that a fall of 0·4 in. was easily capable of absorption by the soil. A very small fraction of it was able to percolate into the drains in the grassland, probably by quick penetration through the fissured ground about the newly drawn mole channels, where percolation could proceed more quickly than absorption by the soil. Two days later the balance in favour of percolation was more marked and the smaller fall of 0·21 in. gave a bigger run-off. Nine days later the next heavy fall of 0·5 in. gave a very much larger amount of percolation and run-off. By this date, however, the soil was becoming fairly moist and percolation was probably taking place from farther afield, so that the flow continued for a longer time, and after a

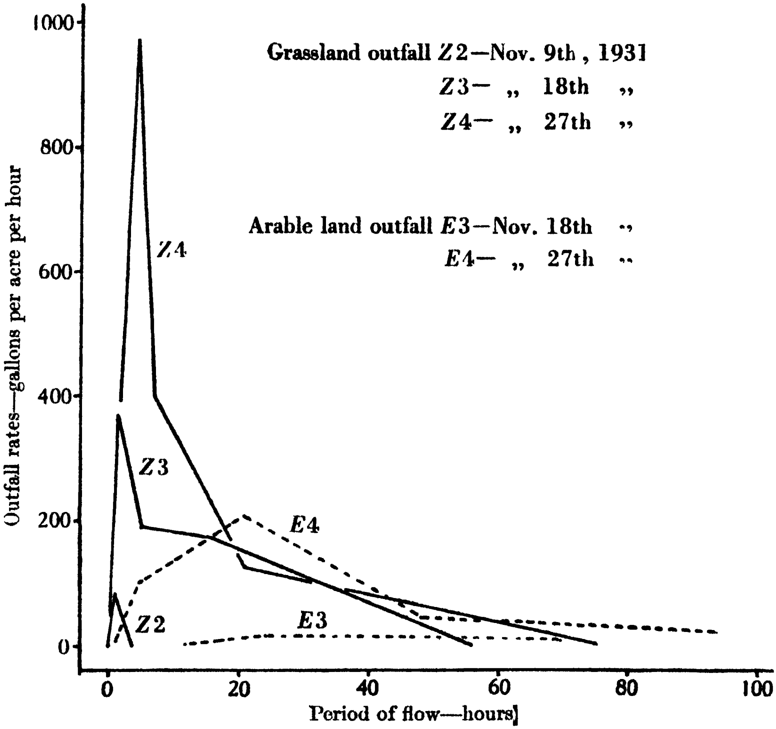

Fig. 2. Comparison of run-off from grass and arable land, on successive occasions.

smaller fall of 0·3 in. on November 27th, the resultant outfall was both more intense and longer in duration. The arable land above *E*, with its recently formed tilth, was able to absorb the falls of rain completely on the first two occasions, and it was only on the third and fourth that any excess became apparent as run-off.

In the above presentation of the data (Table III) no adjustment has been made for differences in the area served by the outfalls. By plotting the records of various complete flows, determinations of the total run-off were made in a number of cases, so that with a knowledge of the various acreages served by the outfalls, a closer comparison can be made, as is shown in Table IV.

Table IV. *Percentage of rainfall evacuated by outfalls.*

Outfall	*B*	*E*	*Z*	*W*	*V*
Area served (in acres)	6·5	5·2	3·9	3·3	1·3
Cropping of soil	Winter beans	Winter wheat	Permanent grass	Permanent grass	Permanent grass
Discharge as % of rainfall (1931):					
Nov. 15th–22nd	6·9	3·1	48·9	—	—
Nov. 22nd–Dec. 6th	49·2	73·5	83·2	—	—
Jan. 13th–23rd	25·4	31·0	54·3	53·6	49·0
April 30th–May 4th	—	53·0	98·0	85·0	—

It will be seen that the trend of these figures is similar to that of Bailey Denton's records, except in so far as rainless periods supervene, when with mole-drain systems, as a rule, outfall ceases and the soil is able, in spite of low evaporation, to recover its absorptive powers to quite a considerable extent. In the instances quoted, the periods December 6th–28th, and January 16th–March 22nd were practically rainless. April was a wet month throughout, so that the soil once more became saturated and the rainfall was again largely cleared via the drains, more so on the grassland than on the arable. Outfalls *Z*, *W* and *V* serve different portions of the same field and, in spite of variations in the general slope of the ground, the results show a fair measure of agreement.

COMPARISONS BETWEEN TILE- AND MOLE-DRAIN SYSTEMS.

In examining the outfall records over the whole season, and comparing events with those dealt with in Bailey Denton's records, certain general points of interest emerge in respect of the various types of drain dealt with. All are characterised by a number of definite flushes, *i.e.* marked rise and fall caused by separate falls of rain. These are set out in Table V.

Table V. *Showing the general type of run-off in tile- and mole-drain systems.*

Season	Soil conditions	Type of drains		Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
1856–7	Light land	Wide parallel, tiled	No. of flushes	—	1	2	1	2	2	0	0	0	—
			„ days without flow	—	0	0	0	0	0	0	0	0	—
1856–7	Heavy land	Close parallel, tiled	„ flushes	—	0	1	2	4	1	0	2	0	—
			„ days without flow	—	31	26	0	0	0	0	0	0	—
1931–2	Heavy grassland	Mole-drained furrows	„ flushes	0	0	4	3	4	1	2	6	9	0
			„ days without flow	30	31	12	19	0	21	22	0	0	24
1931–2	Heavy arable land	Moled 9 ft. apart	„ flushes	0	0	2	2	2	0	0	5	9	0
			„ days without flow	30	31	14	10	0	23	26	0	0	20
1932–3	Heavy grassland	Mole-drained furrows	„ flushes	0	2	4	0	5	5	5	0	1	0
			„ days without flow	30	23	18	10	2	0	0	29	24	30
1932–3	Heavy arable land	Moled 9 ft. apart	„ flushes	0	3	3	0	4	3	2	0	1	0
			„ days without flow	30	10	0	0	0	0	0	0	20	30

Table VI. *Maximum rates of outfall attained by drains.*

Soil conditions	Type of drain	Distance	Depth	Season	Rainfall during drainage season in.	Max. outfall rates—gals. per acre per hour
Light land (Bailey Denton)	Tiles	59 yd.	4 ft. 6 in.	1856–7	10·05	Oct. 12th—66. Dec. 13th—101. Jan. 27th—82. Feb. 7th—65
Heavy land (Bailey Denton)	Tiles	25 ft.	4 ft.	1856–7	10·05	Dec. 13th—41. Jan. 10th—214. Jan. 27th—115. Feb. 7th—52
Heavy land, arable (Cambridge)	Moles	9–10 ft.	2 ft.	1931–2	12·12	Nov. 19th—33. Nov. 28th—206. May 3rd—355
Heavy land, arable (Cambridge)	Moles	9–10 ft.	2 ft.	1932–3	13·43	Oct. 28th—57. Jan. 17th—95. Mar. 18th—93
Heavy grassland (Cambridge)	Moles	3 per furrow	2 ft.	1931–2	12·12	Nov. 19th—360. Nov. 27th—390. May 3rd—1025
Heavy grassland (Cambridge)	Moles	3 per furrow	2 ft.	1932–3	13·43	Nov. 22nd—57. Jan. 16th—370. May 7th—800

Note. As a result of the 1933 drought, none of the drains on the Cambridge University Farm have run during the 1933–4 season, up to the date of writing.

This record is a reflection of the distribution of the rainfall during the drainage season. The flushes are much more marked on heavy land than on light, in mole drains than in tile drains and on grassland than on arable. In the case of the tile-drain records the flow between flushes was continuous, although generally at a low rate. In the case of mole drains, it was not an uncommon occurrence for the drains to cease running when any period free from heavy falls of rain supervened. In all probability, the existence or non-existence of a water table is the chief cause of these differences, as Bailey Denton's light-land records show, but it is suggested that, on his heavier types, it may be the case only so far as the disturbed earth filling the drain trenches is concerned. The existence of such conditions to the extent of 1 sq. ft. in every 25 may have been sufficient to keep the outfalls running slowly for a considerable time after general percolation through the soil had ceased.

The speeds of run-off attained by the various types of drain, as shown by the maximum outfall rates recorded, are instructive. Some of these are set out in Table VI.

THE EFFECT OF VARIATIONS IN THE TREATMENT OF LAND.

The differences in behaviour between light and heavy soils generally, and between arable and grass land on heavy soil, have been indicated. The observations which are the subject of this account seem also to reflect variations due apparently to differences in the treatment of individual fields in the normal course of farm management, and to differences in the climatic conditions from one season to another.

The summer of 1931 was wet. A considerable amount of rain fell in September, but October was characterised by an almost complete absence of rain, so that by the end of the month none of these heavy-land drains had run. Reference to Table II shows that the first small run-off occurred from *Z* following 0·4 in. of rain on November 6th. This outfall was one serving an area of permanent grass which was newly mole-drained on September 18th–20th. It performed again, more vigorously, on the 11th, but it was not until this and the following day that any drainage took place on the arable land as represented by *B*, *E* and *M*. The comparative amounts and rates of outfall have already been discussed, but it remains to add that the areas behind them had all been fallowed throughout the summer but that during the autumn, in accordance with the farming policy adopted, diverse treatments were applied to them individually. A considerable part of the area served by *M* had been reduced to a seedbed in July and sown to grass in August, while the areas behind *B* and *E* were ploughed again in October and sown with beans and wheat respectively early in November. The result of these treatments would be to leave the *B* and *E* areas in a more permeable but, at the same time, drier condition than the *M* area, a combination of circumstances which would enable the soil on them to deal with rainfall by absorption alone for a longer period. In actual fact *M* ran gently on November 11th–13th, *B* trickled on November 12th–16th, *M* ran freely from November 18th onwards, and *B* and *E* ran freely from November 19th onwards.

The 1931–2 drainage season for this land closed in the first week of June after tremendous activity during the preceding wet month of May. Rainfall in September 1932 was fairly well distributed over the month with a total of 1·66 in. October 1st was ushered in with 0·45 in., while falls amounting to 0·85 in. were evenly spread over the period from the 8th to the 11th. Outfall *B* commenced to run on the latter date, after which it continued until April 21st, 1933 (see Fig. 3). It was not until the end of October, during which 3·7 in. of rain fell, that the grassland drains, as represented by *Z*, gave any outfall. This had short runs on the 26th, the 29th and the 31st, after which it was dry again until November 22nd, when 0·31 in. of rain caused it to run vigorously. Thereafter it ran continuously, though with the usual variations, until April 1st. *M* began to run on October 29th and developed a moderate flow by the 31st, continuing for the rest of the season. *E* merely dripped on the 31st and did not give a measurable flow until November 25th, nearly a month later, after 0·41 in. of rain the preceding day. The bean crop above *B* had been removed in August, the ground was ploughed in early September, and a seed-bed for wheat was prepared in early October. When the beans were removed in August the ground was very dry and much cracked. The corn above *E* was harvested in August, the ground was ploughed and harrowed in September and October respectively, and drilled to oats by the middle of the latter month. The hay crop above *M* was removed in June. In examining the circumstances connected with these areas and the order in which the drains began to flow, attention is drawn to the fact that the 1931 cultivations took place after a wet September and resulted in the soil becoming much drier, especially in the tilth layer. The 1932 cultivations, on the other hand, took place earlier and after a drier spell, but under different conditions while they were in progress. Several heavy falls of rain came after ploughing began and before the operation of harrowing was completed. The rain would get below the plough slice more easily so that the subsoil would become moister and much less loss by evaporation would ensue. In particular there were falls on October 1st of 0·45 in., and on the 8th–9th of 0·37 in., all before harrowing took place. *B* began to run on the 11th. The case of *E*, on this argument, should be similar, but in fact it did not begin to run until much later. It was, however, differently treated in that it was ploughed twice in September and drag harrowed twice in October before seeding. On *B* these operations were done once only. Compared with the *B* area, therefore, this land was likely, by evaporation, to get rid of much moisture and show less response to the heavy falls of rain which caused *B* to run.

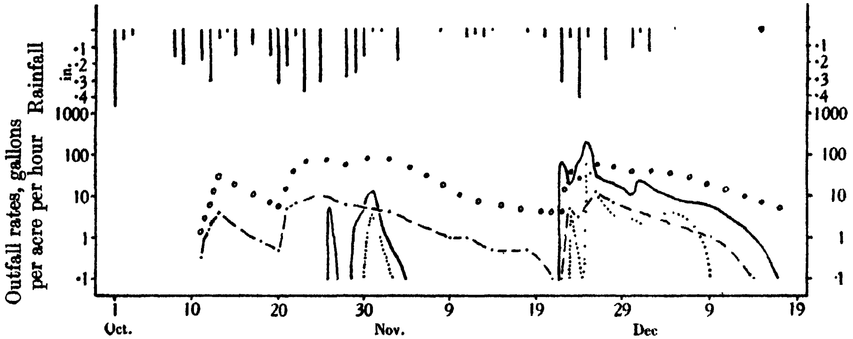

Fig. 3. Commencement of drainage season, 1932–3. Outfall rates plotted on logarithmic scale.

•—•—• Outfall *B*. ooooo Outfall *A*.
——— Outfall *Z*. ••••••• Outfall *M*.

A further instance may be described. Alongside outfall *B* is another, *A*, serving an adjacent area of similar land. During the season 1932–3 this land showed a tendency to become water-logged, and the outfall records of the two areas showed markedly dissimilar behaviour throughout. The beginning of the drainage season is shown in Fig. 3, and the whole story is summarised in Table VII.

Table VII. *Run-off from outfalls* A *and* B, *expressed as percentage of rainfall for the corresponding period.*

Period	% run-off from *A*	% run-off from *B*
Oct. 11th–20th	14·8	0·5
Oct. 21st–Nov. 21st	43·5	4·0
Nov. 22nd–Dec. 31st	52·5	5·3
Jan. 6th–30th	68·8	34·6
Feb. 26th–Mar. 16th	65·6	39·5
Mar. 16th–24th	49·7	45·2

Both outfalls began to run on the same day, but while *B* ran only slowly until January 14th, *A*, serving an area roughly only three-quarters of that served by *B*, flowed freely from the start with several periods of comparatively heavy efflux before that date. Unfortunately, complete data are not available for the early history of these two systems. During 1931–2 *B* only was recorded, owing to the inaccessibility of *A* and its liability to inundation. In the season 1930–1, however, these two were recorded over two separate periods in the spring when they were both running freely, February 11th–20th and April 22nd–May 7th. The outfall rates were identical except at the peaks of the more marked flushes. The mole drains on both had been drawn in January 1931 and both areas were fallowed during that summer. With new drains and similar treatment it was to be expected that similar results would be shown by the outfalls. The divergence at the heaviest rates of flow cannot yet be accounted for. The events of the 1932 season indicate the appearance of new factors, such as have been introduced in the different treatments since 1930. After the fallow of 1931 the *B* area, as described earlier, carried a crop of beans, while *A* was given a second summer fallow. In August 1932 it was noticed that while the *B* stubble was dry and much cracked, the fallow area *A* was covered by a rough tilth. The undisturbed subsoil below the fallow was much moister than that below the bean stubble and cracks were not apparent. Early in September, *B* was ploughed while *A* was broad-shared. As a result, although it would be expected that rain would reach the subsoil in greater quantity on *B* than on *A*, when it did so it would find in *B* conditions conducive to its more effective absorption, while in *A* the subsoil would be already fairly moist and there would be a much better chance of drainage ensuing.

SUMMARY.

1. Some records of tile drain performance by J. Bailey Denton in 1856–7 have been re-examined. The different aspects of drainage in heavy- and light-soil types are indicated.

2. The existence and influence of the movements of the water table in connection with the behaviour of light-land drains are demonstrated. The problem of the water table in heavy land is discussed and the behaviour of field test holes in such circumstances is explained by surface drainage into them.

3. The magnitude of the fluctuations in run-off from heavy land and the need for closer records of outfall performance are stressed.

4. Observations on the behaviour of mole drains on heavy clay land are described. Comparison of grass and arable land records reveals differences analogous to those between heavy and light land. An account

is given of the effects of the advance of the drainage season and of the distribution of rainfall within the season. The nature of the differences in action of tile and mole drains is described.

5. The effects of variations in the agricultural treatment of one soil type on its drainage properties are indicated. Examples are given of the drying out of the soil and subsoil in the absence of a soil mulch, of the power of surface cultivations to keep the subsoil moist, and of the influence of cultivations in drying out the surface soil, together with their effects on the subsequent drainage history of the area involved.

In conclusion the writer wishes to acknowledge his indebtedness to Prof. F. L. Engledow and Mr W. S. Mansfield for their help and criticism since the beginning of this investigation; and to Mr R. K. Kerkham, who surveyed the area concerned and carried out the work of recording the outfalls in 1931–2.

NOTE.

At the time that this paper was written, March 1934, no drains on the farm had run at all during the season 1933–4. Rainfall amounting to 2·21 in. during April, however, including three single days' falls of 0·36, 0·63, and 0·44 in., has at last induced drainage. It is noteworthy that the only drains to run freely have been such of the mole-drain systems, described in this paper, as serve an area which was gyrotilled in the summer of 1933. The light-land drains have (May 15th, 1934) still not run, nor have the mole drains on gault grassland. On the ordinary stubbles and leys of the heavy gault arable land, no drainage has occurred beyond dripping at the outfalls *A* and *B* mentioned above, but outfall *M*, together with three others, all serving mole-drain systems of the same date and all including part of the gyrotilled area, ran freely after the fall of 0·63 in. of rain on April 26th, with a marked flush after 0·44 in. on April 26th. The highest recorded rate on this occasion was 1980 gallons per hour from an outfall serving 10 acres. The flows steadily fell off and all were dry again by May 5th. It is suggested that these events are explained by the production of what is in effect a very deep mulch by the gyrotilling, that this protected the subsoil with its mole drains from drying out, very much on the lines described in connection with *A* (*vide* pp. 364–5), at the same time creating a more permeable topsoil, and so producing the most favourable conditions for draining, within the area under consideration.

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A CHEMICAL STUDY OF SUGAR BEET DURING THE FIRST GROWTH YEAR.

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(With One Text-figure.)

INTRODUCTION.

THE results discussed in this paper are based on the weights and composition of the sugar-beet plant and parts of the plant at eight different stages during its growth. The data provide information on the following points: the intake and translocation of nutrients derived from the soil, and the formation and storage of sugars.

The only work of a similar nature known to us is that of Zitkowski, Potoliet and Reed (1), carried out in 1910 with beet of very low sugar content compared with present-day beet, and that of Wagner (2), carried out in 1927. The former work is of limited value owing to the small number of plants sampled, and the almost complete defoliation of the plants by disease at a vital period during active growth. The latter observer weighed and analysed ten plants only at each date at which the plant was sampled. In our opinion such a sample is too small to be representative as regards weight or for supplying material for analysis.

For the purpose of the experiment, an area of one acre was divided into sixteen plots, and an equal number of plants from each of the plots were removed at approximately 9 a.m. on each sampling date for purposes of analysis. The minimum number of plants taken at any sampling was sixty-four, and the weights of substances referred to later are the actual weights found in this number of plants. This appears the soundest course to adopt, for although the earlier samples contained a larger number of plants, no error is introduced by reducing the weights to those present in the smaller number. On the other hand, however, errors would be magnified if the attempt were made to express the weights present in a larger number of plants. To afford some evidence regarding uniformity in weight of samples of this size, duplicate samples of thirty-two plants were taken at each date, and the weights of leaves and washed roots compared. The difference between samples of this size never exceeded 10 per cent., so that it is unlikely that errors attaching to our samples of double this size are of sufficient magnitude to invalidate the conclusions drawn.

SOIL AND WEATHER CONDITIONS: PROGRESS AND CHARACTER OF CROP GROWN.

The crop was grown at Good Easter, Essex, upon land which had grown wheat in 1931 and barley in 1932. For the 1931 crop, the land received 4 cwt. of superphosphate and 1 cwt. of sulphate of ammonia per acre, and for the 1932 crop 5 cwt. per acre of a compound manure. For the beet crop, 9 tons of dung were applied and ploughed in during the autumn of 1932. In the spring, the land was twice disc harrowed and twice harrowed with a heavy harrow. Before drilling with the beet variety Kleinwanzlegen E. on May 3rd, the land was manured twice and lightly harrowed, and after drilling was thrice rolled and a fine and firm seed-bed obtained. The "artificial" manures applied were 3 cwt. sulphate of ammonia, 4 cwt. superphosphate and 2 cwt. muriate of potash per acre.

The soil is a calcareous clay, and the field is level and unshaded by trees. The seed was drilled at the rate of approximately 15 lb. per acre with a distance between the rows of 22½ in. Singling was carried out between June 1st and 8th to an approximate population of 30,000 plants per acre.

Meteorological data during growth were recorded and a short summary of the effect of the general weather conditions on the crop is given here. For convenience this is divided into the periods between the dates on which the crop was sampled.

Period	
May 31st–June 21st	By the end of the period the plants were well grown and had an average of six leaves. Hours of sunshine, 182. Inches of rain, 1·16.
June 21st–July 5th	The plants grew very rapidly and were of very healthy appearance. Hours of sunshine, 109. Inches of rain, 0·16.
July 5th–19th	Warm and moist weather engendered rapid growth and a fine healthy crop promised. Hours of sunshine, 71. Inches of rain, 1·01.
July 19th–Aug. 2nd	The high temperature of the latter part of July caused wilting during the daytime, and there was considerable yellowing of the leaves by the end of this period. Growth was slow and rather small roots were indicated for the harvest. Hours of sunshine, 117. Inches of rain, 0·09.
Aug. 2nd–16th	Hot and dry weather was again experienced and the yellowing was more pronounced. Little growth appeared to be made. Hours of sunshine, 116. Inches of rain, 0·10.
Aug. 16th–30th	The weather continued hot and dry and little growth was made. Hours of sunshine, 122. Inches of rain, 0·13.
Aug. 30th–Sept. 13th	Weather continued hot and dry, yellowing of the leaves very general but plants free from disease and none "bolting" to seed. Hours of sunshine, 127. Inches of rain, 0·37. Of this 0·20 fell on the day before sampling.

METHOD OF SAMPLING AND PREPARATION OF SAMPLES.

Entire plants were lifted from the soil by means of specially made forks with two hardened steel tines about 15 in. in length.

In this operation, we were favoured by the dry weather conditions, little difficulty being experienced in lifting the roots with, as far as could be judged, little loss of root, and with comparatively little adhering soil.

The plants as lifted were placed upright in deep galvanised iron baths covered with sacking to reduce loss of weight through wilting during the sampling and transport to the laboratory. The time taken from commencement of sampling to arrival at the laboratory never exceeded 1 hour.

The samples were then dealt with immediately. The leaves were removed by cutting flush to the crown of the root and then weighed. Samples for the determination of dry matter and of sugar in the leaves were then weighed out without loss of time. For these purposes, the whole of the leaves were cut up by means of scissors in the case of the plants from the earlier samples, but with the later ones each top was cut lengthwise into four, and a fourth part only from each plant cut up further. The remaining portion of leaves was pulled asunder and wiped with a damp cloth before being cut by scissors, dried and ground to form the sample on which the determinations of substances other than sugar were made. The roots were well washed and dried on cloth and on blotting paper previous to weighing. In the case of the earlier samples the complete roots were minced in a mincing machine, but the larger roots of the later samples were quartered longitudinally and a quarter only passed through the mincer. In both cases, samples for the determination of dry matter and of sugar were weighed without delay. The bulk of the minced material was dried on shallow trays, and ground for further analysis.

METHODS OF ANALYSIS.

Duplicate determinations of the following were made on each sample.

On the comminuted fresh material.

Dry matter. By drying large samples of up to 100 gm. to constant weight at 100° C. (The samples were placed in an air oven at 60°–70° C. for 60 hours, and then transferred to a steam oven.)

Total sugar and reducing sugar. Samples of up to 65 gm. weight were placed in about 300 ml. of boiling 97 per cent. alcohol contained in conical flasks, and the boiling continued under reflux condensers for 24 hours. The alcohol was then poured off and the extraction repeated three times with a like volume of alcohol. The bulk of the alcohol was removed from the complete extracts by distillation until the volume was approximately 75 ml., and then further reduced by the addition of 300 ml. of water and concentrated to 100 ml. by boiling. After removal of proteins from these extracts by basic lead acetate and filtration, the excess of lead acetate was removed by the addition of sodium carbonate and the filtrate made up to a known volume. Reducing sugars were determined on these extracts by the gravimetric method of Fehling, following the usual standardised procedure and using the tables of Elsdon for deducing the weight of sugar from the weight of copper oxide. In the case of the roots, a modification of Benedict's volumetric method, worked out in this laboratory, using methylene blue as internal indicator, was also used to check the gravimetric results.

Total sugars were determined after inversion by 10 per cent. citric acid (immersion in boiling water bath for 1 hour), followed by neutralisation of the acid with sodium hydroxide. The gravimetric and volumetric methods given above were then employed. In the case of the roots, the sugar percentages were further checked by polarimetric determination. At all intermediate stages during the analyses a few drops of toluene were added to the sugar extracts.

On the air dry material.

Dry matter. By drying to constant weight at 100° C.

Nitrogen. By the official salicylic acid modification of the Kjeldahl-Gunning method for total nitrogen in the presence of nitrates.

Phosphoric acid. By destruction of the organic matter by means of sulphuric and nitric acids, precipitation as ammonium phosphomolybdate and reprecipitation with magnesia mixture.

Ash. By ignition at low temperature.

Calcium. By extracting the ash with hot dilute hydrochloric acid, precipitation of the calcium as oxalate and subsequent titration with $N/10$ potassium permanganate.

Potash. By removing all bases other than soda and potash from the extract of the ash obtained as above, by precipitation with barium hydroxide, ammonia, ammonium carbonate and ammonium oxalate, followed by precipitation of the potash as perchlorate.

Silica. By weighing the insoluble material of the ash after extraction with hydrochloric acid.

Table I. *Percentage of dry matter and percentage composition of dry matter of sugar beet at the sampling dates.*

Date 1933	Dry matter	Ash	SiO_2	Silica-free ash	CaO	Cl	K_2O	P_2O_5	N	Total sugars (as cane sugar)	Cane sugar	Reducing sugars
					Whole plant							
May 31st	9·08	24·64	—	—	3·70	—	5·62	1·49	4·35	4·84	3·75	1·09
June 21st	9·46	22·83	0·96	21·87	3·45	1·15	5·69	1·17	4·15	10·67	—	—
July 5th	9·63	21·09	0·67	20·32	2·49	2·41	7·06	1·03	3·46	27·20	21·27	5·73
July 19th	12·50	16·03	0·43	15·60	2·21	2·25	4·48	0·74	2·88	30·06	24·89	5·17
Aug. 1st	13·71	12·87	0·28	12·59	1·58	1·88	3·55	0·72	2·03	39·32	33·52	5·80
Aug. 16th	18·01	10·20	0·24	9·96	1·30	1·44	2·42	0·72	1·36	49·78	44·60	5·18
Aug. 31st	20·26	8·60	0·15	8·48	1·17	0·98	2·14	0·62	1·16	53·69	48·95	4·74
Sept. 13th	21·80	—	—	7·33	0·99	0·76	2·06	0·35	1·11	53·84	49·96	3·88
					Leaves							
May 31st	8·60	27·43	1·82	25·61	3·87	—	6·46	1·68	4·75	4·19	3·23	0·96
June 21st	8·85	25·47	0·85	24·62	4·14	1·32	6·01	1·22	4·61	4·62	—	—
July 5th	8·45	25·99	0·80	25·11	3·41	3·20	8·41	1·01	4·07	11·46	4·28	7·18
July 19th	10·68	22·78	0·49	22·29	3·30	3·44	5·91	0·79	3·88	9·55	2·31	7·24
Aug. 1st	10·59	21·03	0·36	20·67	2·63	3·48	5·37	0·77	3·00	11·61	2·03	9·58
Aug. 16th	13·05	20·97	0·31	20·66	2·67	3·46	4·55	0·78	2·18	15·68	4·32	11·36
Aug. 31st	14·21	21·00	0·23	20·87	2·73	2·87	5·08	0·75	2·02	14·57	3·23	11·34
Sept. 13th	14·97	—	—	19·26	2·47	2·54	4·93	0·49	1·94	15·63	4·88	10·74
					Roots							
May 31st	14·40	8·96	—	—	2·10	—	1·36	0·47	2·70	9·70	7·20	2·50
June 21st	12·84	12·52	1·38	11·14	0·82	0·49	4·48	0·96	2·37	34·05	33·28	0·77
July 5th	13·65	10·77	0·38	10·39	0·54	0·73	4·22	1·09	2·16	60·37	57·04	3·33
July 19th	16·51	5·94	0·35	5·59	0·60	0·39	2·37	0·65	1·37	60·56	58·44	2·12
Aug. 1st	19·49	4·65	0·21	4·44	0·51	0·25	1·71	0·67	1·04	67·38	65·21	2·17
Aug. 16th	23·80	3·32	0·19	3·13	0·42	0·15	1·06	0·68	0·84	71·55	70·32	1·23
Aug. 31st	25·10	2·99	0·12	2·87	0·46	0·12	0·82	0·55	0·77	71·40	69·63	1·77
Sept. 13th	26·53	—	—	2·66	0·40	0·06	0·94	0·29	0·77	68·76	67·59	1·17

Chlorine. By wet oxidation of the organic matter with nitric acid and potassium permanganate in the presence of excess of silver nitrate (as in the method of Davies (3)), and titration of the excess of silver with potassium thiocyanate, using iron alum as indicator.

PERCENTAGE COMPOSITION OF DRY MATTER.

Discussion of Table I.

Whole plant.

It will be observed that the percentages in the dry matter of the plant of nutrients derived from the soil all decreased from the date of the third sampling (July 5th). With the exception of chlorine and potash, the decrease was noted from the date of the first sampling (May 31st).

The decrease in percentage is, of course, in the main due to carbon being assimilated at a higher rate than these nutrients, as is illustrated by the marked increase in the percentage of sugars. The percentages of all nutrients fell to about one-third of their maxima, but it may be noted that a greater relative decline occurred in the case of phosphoric acid. Evidence is brought later to show that this greater decline is due to partial loss of this nutrient from the plant. The percentage of reducing sugars in the dry substance maintained a steady level from the time the plant was "singled"—probably the time it became self supporting—until the final harvest.

Leaves.

The changes in composition of the dry matter of the leaves were similar but less marked than those noted in the whole plant. The concentration of total sugars reached a maximum by mid-August, while that of cane sugar was fairly constant throughout growth.

Roots.

Although the percentages of nutrients fell markedly, it may be noted that this did not occur until the third sampling (early July) in the case of potash, phosphoric acid and chlorine. In other words, until this period, assimilation of these nutrients occurred at relatively higher speed than that of sugar translocation from the leaves. The maximum content of sugar in the dry substance was reached by the beginning of August, and then remained remarkably constant.

Table II. *Weights in grams of substances in sixty-four sugar beets (whole plant).*

Date 1933	Green matter	Dry matter	Ash	SiO_2	Silica-free ash	CaO	Cl	K_2O	P_2O_5	N	Total sugars (as cane sugar)	Cane sugar	Reducing sugar
May 31st	38·42	3·49	0·86	—	—	0·129	—	0·196	0·052	0·152	0·169	0·131	—
June 21st	1,301	123·0	28·08	1·18	26·87	4·25	1·42	7·00	1·44	5·11	13·12	—	—
July 5th	7,609	733·0	154·60	4·90	149·70	18·23	17·66	51·76	7·59	25·35	199·40	155·9	43·5
July 19th	23,972	2996·0	480·50	13·00	467·50	66·33	67·44	134·40	22·13	86·36	900·80	745·7	155·1
Aug. 1st	30,118	4128·0	531·30	11·76	519·50	65·09	77·56	146·40	29·95	83·79	1626·00	1383·0	243·0
Aug. 16th	37,376	6733·0	686·40	15·94	670·56	87·58	97·31	162·80	48·57	91·8	3352·00	3003·0	349·0
Aug. 31st	36,380	7372·0	633·90	11·37	624·90	86·14	72·21	158·10	45·58	85·58	3958·00	3608·0	350·0
Sept. 13th	41,963	9146·0	—	—	670·40	90·17	69·47	188·70	31·94	101·16	4923·00	4569·0	354·0

Table III. *Weights in grams of substances in sixty-four sugar beets (leaves).*

May 31st	35·37	3·05	0·82	0·05	0·77	0·12	—	0·19	0·05	0·14	0·126	0·10	—
June 21st	1,104	97·7	24·88	0·83	24·05	4·04	1·30	5·87	1·20	4·51	4·51	—	—
July 5th	5,880	497·0	129·20	4·00	125·20	16·95	15·93	41·80	5·02	20·23	56·97	21·28	25·69
July 19th	16,676	1791·0	408·90	8·78	400·10	59·10	62·66	105·80	14·24	69·82	171·00	41·40	129·60
Aug. 1st	19,568	2072·0	435·70	7·46	428·20	54·50	72·26	111·30	16·03	62·22	240·60	42·00	198·60
Aug. 16th	20,103	2622·0	549·90	3·13	541·80	70·11	90·82	119·30	20·50	57·23	411·10	113·10	298·00
Aug. 31st	16,163	2296·0	482·10	5·28	479·30	62·69	66·07	116·60	17·41	46·50	334·50	74·16	260·30
Sept. 13th	17,186	2573·0	—	—	495·50	63·54	65·39	126·90	12·81	50·09	402·10	125·50	276·60

Table IV. *Weights in grams of substances in sixty-four sugar beets (roots).*

May 31st	3·05	0·44	0·039	—	—	0·009	—	0·006	0·002	0·012	0·043	0·031	0·012
June 21st	197	25·3	3·17	0·35	2·82	0·21	0·12	1·13	0·24	0·60	8·61	8·42	0·19
July 5th	1,729	236·0	25·42	0·90	24·52	1·28	1·73	9·96	2·57	5·12	142·40	134·60	7·80
July 19th	7,296	1205·0	71·58	4·22	67·36	7·23	4·78	28·56	7·89	16·54	729·80	704·30	25·50
Aug. 1st	10,550	2056·0	95·61	4·32	91·29	10·59	5·30	35·16	13·92	21·57	1386·00	1341·00	45·00
Aug. 16th	17,273	4111·0	136·50	7·81	128·70	17·47	6·49	43·53	28·07	34·59	2941·00	2890·00	51·00
Aug. 31st	20,217	5076·0	151·80	6·09	145·60	23·35	6·14	41·47	28·17	39·08	3624·00	3534·00	90·00
Sept. 13th	24,777	6573·0	—	—	174·90	26·63	4·08	61·79	19·13	51·07	4521·00	4443·00	78·00

WEIGHTS OF SUBSTANCES IN PLANT DURING GROWTH.

Discussion of Table II.

In commenting on this table, we have given consideration to the fact that from mid-July until our final sampling the season was abnormally dry, and that this resulted in the crop attaining maturity at an earlier date than usual. From consideration of the meteorological data and the field observations given earlier, we are of opinion that our final sample represented mature but prematurely ripened beet. Accordingly, we should expect the same general changes to be undergone in the same general order by sugar beet grown in more normal seasons, but that these would occur later.

It will be seen that assimilation of phosphoric acid, lime and chlorine ceased a month before maturity was reached. It is probable that assimilation of potash and nitrogen proceeded until maturity; there is little doubt that this was the case with potash, and if, as appears likely, the sixth sample contained an undue number of plants larger than the average, it would also be true of nitrogen assimilation.

A striking contrast in the periods of the plant's history at which assimilation of nutrients is proceeding rapidly is shown in the case of phosphoric acid and nitrogen. Thus at 7 weeks after singling, the plant contained less than one-half of its maximum quantity of phosphoric acid, but four-fifths of its maximum quantity of nitrogen.

Assuming that this is normal, it is obvious that the plant is very dependent on supplies of available nitrogen in its earlier stages. Losses of phosphoric acid and chlorine from the plant are noted during the last month. These losses are considerable, amounting to approximately one-third of the maxima, and are greater than could be caused by sampling errors.

It may be noted that Wagner observed no loss of these substances, but, on the other hand, recorded a loss of calcium. It is of interest to consider if the loss of phosphoric acid undergone by this biennial plant in its first year of growth may be due to it not being needed for seed formation.

The phenomenon of nutrient losses by living plants has been alluded to and discussed in some detail by two of us (4) in the case of the wheat plant. Such losses have been shown to occur in other plants by several observers and, in the case of *Phalaris tuberosa*, Richardson, Trumble and Shapter (5) indicate that the loss of potash undergone by this plant was by actual excretion to the soil.

In the light of these observations, the question raised by Sekera (6) of luxury consumption of nutrients by plants is of great interest.

Discussion of Tables III and IV.

Leaves (Table III). The chief point to be noted is that potash was moving into the leaf until harvest, but after July the amount entering was very greatly reduced. With the exception of nitrogen, all other nutrients were present in maximum quantity by mid-August; nitrogen reached its maximum a month earlier. A marked decrease in the amounts of phosphoric acid and chlorine occurred after the maxima were reached. We can only presume that these substances were returned to the roots, since there was no rain to cause leaching, even if it were possible for them to be leached.

As far as sugars are concerned, it will be noted that no increase in amount occurred during the last month of growth. When this is compared with the increase which occurred in the plant as a whole, it can only be taken to indicate that the manufacture and translocation of sugars proceeded at equal rates during this period.

Roots (Table IV). In the case of calcium, potash and nitrogen, the amounts increased until maturity, but phosphoric acid and chlorine reached their maxima by mid-August. It may be noted that after this date the roots lost approximately 9 gm. of phosphoric acid and 2·5 gm. of chlorine, whereas in the same period the leaves lost approximately 8 gm. and 25·5 gm. respectively. If loss by leaching is considered impossible, the only interpretation is that phosphoric acid and chlorine are excreted from the root faster than they are returned to it from the leaves.

DISTRIBUTION OF NUTRIENTS BETWEEN LEAVES AND ROOTS.

Discussion of Fig. 1.

The following points are brought out by Fig. 1. In the young plant, before singling, 90 per cent. of the dry matter of the plant was contained in the leaves. This fell progressively to 28 per cent. by the time the plant was mature. During the same period, the distribution of cane sugar in the leaves fell from 76 to 3 per cent.; the latter figure was, in fact, reached by the beginning of August, but thereafter remained constant.

The columns show the preponderance of reducing sugars in the leaves, and the marked constancy in their distribution throughout growth.

The opportunity was taken on two of the sampling dates to obtain data for the distribution of sugars in parts of the leaf. On the first sampling date, when the weight of laminae minus the midribs was approximately double that of the midribs, the composition of the sugars was 83 and 90 per cent. respectively of cane sugar. Later in the season, when the leaves were fully developed, and the midribs double the weight of the remainder of the leaves, the percentage of cane sugar in the total sugars was 37 in the laminae and 18 in the midribs. These figures are of interest in connection with questions of the nature of the sugar first synthesised, and it is unfortunate that more observations from this aspect were not made.

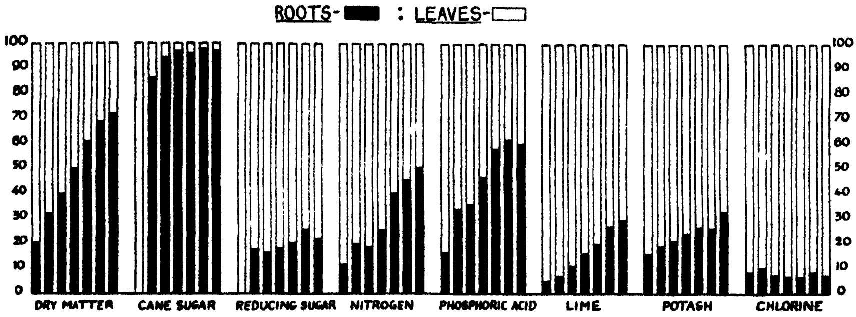

Fig. 1. Percentage distribution of substances in roots and leaves during growth.

The large amount of the total chlorine contained in the leaves, and its constancy at about 92 per cent. throughout growth, is worthy of comment, and may raise interest and speculation as to its function in the leaf. No correlation between chlorine and potash is noted, the latter being present in larger amount in the root, and increasing towards maturity.

Phosphoric acid and nitrogen are contained in the roots in much larger relative amounts than other soil nutrients, especially is this the case with the approach of maturity.

SUMMARY.

1. An account has been given of the composition and weights of nutrients and sugars in sixty-four sugar beet plants from just before singling until maturity. The assimilation, translocation and distribution of these have been discussed.

2. At about singling, the leaves contained 90 per cent. of the dry matter and 76 per cent. of the sugars of the plant, whereas, at maturity, the figures were 28 and 3 per cent. respectively.

3. The percentage of reducing sugars in the dry substance of the complete plant maintained a steady level throughout, as was also the case with cane sugar in the leaves. The highest percentages of sugars in

the dry matter of both leaves and roots were attained by early August. Evidence is produced to show that, although in the plant as a whole carbon assimilation proceeded more quickly than the intake of soil nutrients, until early July the rate of translocation of carbon to the roots did not equal the rate of intake of soil nutrients by the latter.

4. Assimilation of phosphoric acid, lime and chlorine ceased a month before maturity was reached, whereas that of nitrogen and potash proceeded until the end.

5. A very marked contrast in the rate of assimilation of nitrogen and phosphoric acid was observed, and the dependence of the plant on available nitrogen is indicated.

6. Considerable losses of phosphoric acid and chlorine were observed during the last month of growth by both leaves and roots. Presumptive evidence is brought to show an excretion of these substances from the roots.

7. The large and constant proportion of the total chlorine which is contained in the leaves, viz. 92 per cent., is commented on.

We are indebted to Mr H. W. Simmons, N.D.A., of the Crop Testing Station at Good Easter, for the meteorological notes and observations on the state of the crop.

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ON THE YIELDS AND COMPOSITION OF MEADOW HAY FROM CERTAIN OF THE PALACE LEAS PLOTS AT COCKLE PARK.

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Although many reports of short-term manurial trials on meadow hay are to be found in agricultural literature, there are few experiments of this kind which have been adequately maintained over a long period of years, and are still in existence. The value of long-continued treatment needs no emphasis; the cumulative effects of the fertilisers employed usually accentuate the yield and quality differences produced, while the usefulness of means derived from a large number of results is obvious. Among the few recent communications which deal adequately with the long-continued manuring of meadow land, Crowther and Ruston (1) and Jacques (2) have described the influence of various dressings on the productivity of permanent hay plots which have been under uniform treatment since 1899, at the Manor Farm, Garforth. The soil upon which these plots are situated is a light loam resting upon sandstone of the Middle Coal Measures series. As a number of plots under similar treatment, but on soil of an entirely different type, have been in existence at Cockle Park for an even longer period, it may be of interest to summarise the available information as to the effects on yield and quality which have been induced by different manurial treatments at this latter centre.

The Palace Leas hay plots were laid down in 1897 on old grassland. These plots are sixteen in number, and were originally each half-an-acre in area. In 1919 one-third of the field was ploughed out, the size of individual plots being thus reduced to one-third of an acre. The soil is a clay loam which varies from 8 to 15 in. in depth, and overlies stiff boulder clay. Chemical analyses of soil samples drawn from selected plots were made by Collins (3) in 1906, but the soils of this field have not been subjected to any examination on modern lines.

It is interesting to note that Palace Leas was initially in better condition than the adjoining Tree Field; the mean annual hay crop yielded by the control plot, during the first nine years of experiment, was 19 cwt. per acre, as against 8½ cwt. on the untreated plot of Tree Field.

The present investigation has been confined to nine plots only; the treatments applied to these plots are tabulated below:

Table I. *Manures* per acre applied annually.*

(Superphosphate used in alternate years instead of basic slag between 1897 and 1906.)

Plot		Plot	
2	8 tons dung	11	150 lb. sulphate of ammonia
6	Untreated		100 lb. muriate of potash
7	150 lb. sulphate of ammonia	12	300 lb. basic slag
8	300 lb. basic slag		100 lb. muriate of potash
9	100 lb. muriate of potash	13	150 lb. sulphate of ammonia
10	150 lb. sulphate of ammonia		300 lb. basic slag
	300 lb. basic slag		100 lb. muriate of potash

* Dung applied in autumn, and artificial fertilisers, other than sulphate of ammonia, in early winter. Sulphate of ammonia applied in April.

The economic aspects of the above treatments have been fully dealt with elsewhere (3), and no further reference will be made to them.

YIELDS.

The mean yields of hay for five-year periods between 1897 and 1931, together with the yields for 1932, and the mean for the whole period of the experiment up to that year, are shown below.

Table II. *Yields of hay in cwt. per acre.*

	Mean of five-year periods								Mean of 36 years
Plot	1897–1901	1902–6	1907–11	1912–16	1917–21	1922–6	1927–31	1932	1897–1932
2	33·0	40·1	39·4	44·8	39·4	45·6	46·1	38·3	41·1
6	20·7	16·4	19·8	20·9	17·4	19·4	20·0	32·3	19·6
7	28·3	22·0	22·3	22·1	20·8	23·6	20·3	37·8	23·2
8	25·7	23·4	25·3	27·8	20·8	26·7	29·2	34·3	25·8
9	17·3	12·7	16·9	17·2	16·2	18·1	16·7	29·0	16·8
10	32·4	30·0	29·3	31·9	26·6	30·7	33·1	38·5	30·8
11	24·6	18·2	21·3	21·6	20·2	25·1	22·9	35·8	22·4
12	26·3	24·3	27·2	28·3	22·4	30·2	34·0	34·5	27·7
13	31·3	29·8	30·5	32·9	28·0	34·5	36·3	39·0	32·1

When the relative merits of the plots are considered on the basis of mean yields during thirty-six years, it is seen that plot 2, which has received an annual dressing of 8 tons of dung per acre, is the best plot of the series; the difference of 9 cwt. per acre which exists between the means of plots 2 and 13 respectively is almost certainly of high significance. If well-rotted farmyard manure be considered to contain 0·61 per cent. nitrogen, 0·45 per cent. phosphoric acid, and 0·49 per cent. potash, 8 tons will supply approximately 110, 80 and 88 lb. respectively of the three constituents, as against 30, 50 and 50 lb. in the complete mixture of fertilisers applied to plot 13. The relative superiority of plot 2 may be explained on these grounds alone. If the dunged plot be excepted, the heaviest yields have been obtained when basic slag has been used alone, or with one or more other artificial fertilisers. Of the four plots concerned, that which has received a complete dressing has given the highest mean yield, while the elimination of any one component of the mixture has had a depressing effect. As between sulphate of ammonia and muriate of potash, the omission of the former has produced the larger adverse result. The use of sulphate of ammonia alone produced small increase over the mean yield of plot 6 (control). Muriate of potash alone has depressed yield and, in conjunction with sulphate of ammonia, reduced the efficiency of the latter fertiliser. The failure of muriate of potash under these circumstances may be due to an acid soil reaction which is not evident when the fertiliser is used with basic slag. In so far as comparison is possible, these results are in agreement with the findings of Crowther and Ruston (1), who obtained only slight increases in the mean yield of sixteen seasons, as the result of applying 130 lb. of sulphate of ammonia per acre. They state that the use of sulphate of ammonia alone has proved very unsatisfactory. Plots which received dung only showed substantial increases over those which received artificial fertilisers. The omission of potash from a complete mixture of artificial fertilisers resulted in a decrease which was slight and comparable to that obtained at Cockle Park.

It is doubtful whether any considerable significance can be attached to the apparent year-to-year variations in the yields of individual plots, for the data concerning time of cutting, methods of weighing, etc., is incomplete. On plot 2 there appears to have been marked yield increase immediately following on the first five-year period, but this early improvement has not been progressive, and the hay weights have remained reasonably constant since 1902. This effect has not occurred on any of the remaining plots.

COMPOSITION OF HAY.

Analyses made by Collins (3) in 1900, 1905 and 1908 of samples from certain of the plots are given in Table III.

A further series of samples was obtained by the writers on July 20th, 1932, the plots having been mown on the previous day. With a view to eliminating soil heterogeneity in one direction every plot was divided into five equal blocks, from each of which random analytical samples were obtained. The material was conveyed to the laboratory in seed bags, air-dried, and ground in a power mill.

Table III.

Date of analysis ...	1900								1905					1908	
Plot ...	6	7	8	9	10	11	12	13	2	6	8	12	13	6	13
True protein	6·40	6·30	6·91	6·47	8·29	6·66	8·56	9·14	6·71	6·63	6·64	7·52	6·91	8·07	9·15
Amides	2·34	2·03	1·76	2·21	2·31	1·71	2·16	1·16	0·62	0·87	2·21	1·53	1·17	0·59	0·92
N-free extractives	51·82	52·64	46·03	48·04	46·80	50·48	48·38	40·59	55·76	57·36	56·06	54·27	58·21	36·21	47·67
Crude fibre	31·16	30·92	34·85	32·32	31·80	32·02	29·58	37·97	29·97	28·32	27·62	28·63	27·06	48·21	34·79
Ash	8·28	8·11	10·45	10·96	10·80	9·13	11·32	11·14	6·94	6·82	7·47	8·05	6·65	6·92	7·47
Silica	4·27	3·82	3·76	5·72	4·32	4·79	3·85	3·84	1·67	2·62	2·24	2·05	1·45	2·58	1·49

Table IV.

	Plot								
	2	6	7	8	9	10	11	12	13
Crude protein	7·92	8·40	8·04	7·85	8·09	7·99	7·55	9·53	7·95
Pepsin-HCl soluble protein	5·71	6·10	5·73	5·63	5·81	5·89	5·34	7·13	5·79
Percentage digestibility	72·06	72·62	71·23	71·83	71·84	73·70	70·76	74·91	72·82
Ether extract	1·36	1·41	1·68	1·92	1·52	1·69	2·19	2·02	2·21
N-free extractives	53·67	52·35	52·47	52·55	53·08	54·25	54·14	50·58	52·68
Crude fibre	31·81	32·32	33·34	31·46	32·10	30·60	32·91	31·12	31·42
SiO_2-free ash	3·90	3·72	3·37	4·21	3·72	3·82	2·22	5·19	4·18
Lime (CaO)	0·427	0·388	0·263	0·639	0·351	0·526	0·138	0·789	0·446
Phosphoric acid (P_2O_5)	0·503	0·410	0·418	0·601	0·395	0·625	0·289	0·692	0·616

Total crude protein, ether extract, crude fibre, ash and mineral constituents were determined by the usual methods. Duplicate 2 gm. samples for the determination of moisture were always weighed at the same time as portions required for other analytical purposes. Moisture contents were based on the loss of weight sustained during an arbitrary drying period of 24 hours in an electric oven at 100° C. The digestibility of the crude protein was determined by the method of Wedemeyer, 2 gm. of the sample being digested with pepsin-HCl solution for 48 hours at 37° C.

Results. The results shown in Table IV are means from the replicate samples; individual analytical results are given in the Appendix.

Crude protein. The analysis of variance appertaining to the crude protein results is shown below (Table V).

Table V.

Variance	Degrees of freedom	Sum of squares	Mean square	Standard deviation	$\frac{1}{2}\log_e$ mean square	Z	P
Plot	8	12·8296	1·6037	—	1·3863	1·2707	$<0·01$
Sampling	4	0·4064	0·1016	—	—	—	—
Error	32	4·0323	0·1260	0·355	0·1156	—	—
Total	44	17·2683	—	—	—	—	—

As the use of the *Z* test shows that variance due to treatment is significantly greater than that due to error, further statistical treatment is applicable. A difference of 0·519 between the plot means is necessary for significance ($t = 2·306$). It appears, therefore, that plots 2, 7, 8, 10, 11 and 13 do not differ significantly amongst themselves in respect of crude protein content, but that they are all significantly lower than the remaining three plots, viz. 6, 9 and 12. As shown in Table I, all but one of the former have received nitrogen either as sulphate of ammonia or dung. On the other hand none of the latter three plots have received nitrogen in any form. Plot 12, which has been dressed annually with basic slag and muriate of potash, is outstanding, the advantage which it shows over all other plots being highly significant.

Percentage digestibility of protein. Similar statistical treatment to that applied above showed that the difference between plot means for significance was 2·064. Hay from plot 12 is seen to have a higher digestibility than that from any other plot except 10. It will be noted that the use of muriate of potash and sulphate of ammonia respectively with slag, as applied to the above plots, has produced hay of materially higher digestibility than when slag alone was used, although the difference between percentage digestibilities falls just short of significance. Plot 11 would appear to have the lowest digestibility of the series but is, in fact, no poorer than plots 2, 6, 7, 8, 9 and 13. There is a fairly well marked inverse relationship between digestibility and fibre content.

Ether extract. The variance due to treatment did not prove to be significantly greater than that due to error, hence no valid conclusions can be drawn from the plot means.

Crude fibre. With a difference of 1·312 between plot means necessary for significance, plots 6, 7, 9 and 11 do not differ in respect of fibre content, but are significantly higher than all other plots in the series. Plot 7 has produced hay of high fibre content, but plot 2 which has received dung only, and might have been expected to behave similarly, has significantly less fibre.

Lime (CaO). Plot 12 has a lime content which is significantly higher than any other recorded (difference for significance = 0·150). All dressings which supply lime have produced hay of adequate lime content, slag having proved somewhat superior to dung in this respect. The application of sulphate of ammonia in conjunction with either basic slag or muriate of potash has reduced the efficiency of the latter fertilisers. The sulphate of ammonia-muriate of potash combination has again exerted markedly deleterious effects on quality.

Phosphoric acid (P_2O_5). It will be observed that, when the plots are considered in relation to the phosphoric acid content of the hay produced, they fall into four fairly distinct groups. Plots 8, 10, 12 and 13, all of which have received basic slag with or without some additional fertiliser, cannot be separated (difference for significance = 0·081). The application of muriate of potash, sulphate of ammonia, or both simultaneously with basic slag, has therefore had no effect, beneficial or otherwise, on the uptake of phosphoric acid. Hay from plot 2 (dung only) contains significantly less phosphoric acid than the above, but more than any of the remaining plots. It is noteworthy that the foregoing five plots are in the same order in respect of both lime and phosphoric acid content. Plots 6, 7 and 9 show no real differences, hence the use of muriate of potash or sulphate of ammonia alone has been without effect. The combined use of muriate of potash and sulphate of ammonia has again had a markedly adverse influence.

Plot 12 which has received basic slag and muriate of potash must be considered to be the best plot of the series, having produced hay well supplied with mineral constituents and true protein, and containing relatively little crude fibre. Three other plots, viz. 8, 10 and 13, which received basic slag with or without the addition of other fertilisers, have yielded hay of quality not markedly inferior. Those plots which received applications of one or more non-phosphatic artificial fertilisers, viz. 7, 9 and 11, have produced hay of comparatively poor quality. Of these last plots, No. 11 is definitely the worst, being poorer than any other in all the important constituents except fibre. Plots 2 and 6 occupy an intermediate position.

It is obvious that the differences considered above include possible fertility variations in a direction at right angles to the main axes of the plots, in addition to treatment effects. In view of the care taken when the plots were originally laid down, and the homogeneity shown to exist in a direction parallel to the main axes, it was thought that plot-to-plot differences might justly be attributed to treatment alone.

The analyses made by Collins in 1900, 1905 and 1908, and shown in Table III, are incomplete, only two of the plots having been sampled in all three years. While the results obtained are somewhat conflicting, plots 12 and 13 must be considered to have done best; plots 8 and 10 are, however, not markedly inferior. It would appear therefore that this group of four plots, which have received basic slag alone or in conjunction with some other fertiliser, produced hay which, in the three seasons referred to above, was superior to that from plots under other treatments. It is not possible to draw any conclusions concerning the respective merits of these latter plots (2, 6, 7, 9 and 11). The analytical results obtained in 1932, and discussed above, confirm the superiority of the slag-treated plots, and appear to allow of some differentiation between the remainder. The variations in the quality of the hay which have been shown to exist are probably in large part due to changes in the botanical composition of the herbage effected by the long-continued use of different fertilisers. No botanical examination of the swards has been made in recent years, but the results of analyses carried out in 1905 showed that there had already been substantial increase in the numbers of leguminous plants, and a corresponding decrease in the grasses, in plots 8 and 12. On plots 10 and 13 the effects of the basic slag had been nullified by the use of sulphate of ammonia, and no increase in the clovers was evident. These effects are likely to have been accentuated during the intervening period, and probably account for the fact that plots 8 and 12 produce hay of high protein content, while 10 and 13 are less satisfactory in this respect. The fact that all of the foregoing plots are comparatively rich in lime and phosphoric acid may be accounted directly to the use of basic slag. There has been very little change in the character of the herbage on plot 2, despite the fact that the dung applied contained minerals comparable in amount with those in certain of the artificial fertiliser mixtures used on other plots. The adverse effects on quality induced by the fertilisers applied to plots 7, 9 and 11 are probably due to the fact that all of these fertilisers are capable of aggravating a pre-existing acid soil reaction, and have indirectly exerted a severely depressing effect on the leguminous components of the herbage. The poor quality of the hay may also be due, in some measure, to the entire absence of lime and phosphoric acid from the fertiliser dressings, and to the reduced amount of soil calcium available to the herbage as a result of increased acidity.

The feeding value of hay from some of the plots was estimated by Middleton in 1900–1, and again by Gilchrist in 1906 (3) by means of feeding trials. The latter trial included more of the plots with which the present investigation is concerned, and a brief account may be of interest. Duplicate pens, each of four sheep (half-bred wethers), were under experiment between November 23rd and January 27th. The daily ration for each sheep is stated to have been 8 lb. swedes throughout, ½ lb. cake (⅓ decorticated cotton cake and ⅔ Bombay cotton cake) until December 21st, ¾ lb. cake from December 22nd to January 10th, and 1 lb. cake from January 11th to January 27th. Each lot received, in addition, hay from the various plots to the extent of 1½ lb. until December 3rd, 2 lb. from December 4th until January 1st, and 1½ lb. from January 2nd until the close of the experimental period. The swedes and cake fed were considered to provide maintenance for sheep of the type and weight used, so that the live-weight increases produced reflected the varying qualities of the hay. The average weekly gains in live weight per sheep (lb.) produced by hay from five of the plots were as follows:

Plot ...	2	6	8	12	13
Average weekly gain ...	2·04	1·78	2·07	2·26	1·98

The usefulness of analytical figures, such as those shown in Table IV, for the purpose of estimating feeding value, is admittedly limited. It may be noted, however, that the values of the hay samples when assessed on this basis are not in the same order as that indicated by the feeding trial referred to. Whilst the plot 12 hay is outstanding in both cases, analysis points to markedly higher feeding value for the hay from plots 6 and 13 than is given by the feeding trial.

EFFICIENCY OF MANURIAL TREATMENTS AS MEASURED BY PRODUCTION OF DIGESTIBLE PROTEIN, LIME AND PHOSPHORIC ACID IN LB. PER ACRE.

In the absence of adequate digestibility data, the weights per acre of digestible protein, lime and phosphoric acid produced would appear to afford a fairly accurate means of assessing the relative efficiencies of the different manurial treatments. The calculated yields per acre of the above three constituents are shown in Table VI.

Table VI.

Plots	Digestible protein (lb. per acre)	Lime (CaO) (lb. per acre)	Phosphoric acid (P_2O_5) (lb. per acre)
2	207·9	15·5	18·3
6	187·3	11·9	12·6
7	205·9	9·5	15·0
8	183·6	20·8	19·6
9	160·4	9·7	10·9
10	215·9	19·3	22·9
11	181·7	4·7	9·8
12	234·2	25·9	22·7
13	215·0	16·6	22·9

It will be noted that the use of basic slag and muriate of potash, as on plot 12, has yielded the most satisfactory results. The addition of sulphate of ammonia, or the substitution of muriate of potash by this fertiliser, has somewhat reduced the efficiency of the treatment. All of the three foregoing treatments may be considered to have given better results than the use of dung. On the other hand the latter was superior to sulphate of ammonia or basic slag when applied alone. Two treatments, viz. those applied to plots 9 and 11 (muriate of potash only, and sulphate of ammonia with muriate of potash respectively), have depressed productivity below that of the control plot.

SUMMARY.

1. The available information as to the yields and composition of hay from the Palace Leas plots at Cockle Park has been summarised.
2. The use of basic slag alone, or in conjunction with other artificial fertilisers, is shown to have been the most effective treatment for the production of high quality as measured by analysis. Manurial dressings from which the phosphatic component has been omitted have had a depressing effect.
3. The results of feeding trials are not wholly in agreement with those of analysis, but confirm the effectiveness of phosphatic fertilisers.

4. The annual application of 8 tons of dung per acre has produced heavier yields than any other of the treatments under consideration. Dressings including basic slag, come next in effectiveness. Muriate of potash, when used alone, is the only treatment which has depressed yield below that of the control plot.

5. When the relative efficiencies of the manurial treatments are assessed on the basis of the total weights of digestible protein, lime and phosphoric acid produced per acre, the use of basic slag together with sulphate of ammonia and muriate of potash, or with either of the latter, has given the best results.

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APPENDIX.

Composition of hay samples (per cent. of dry matter).

Constituent	Plot								
	2	6	7	8	9	10	11	12	13
Crude protein	7·87	8·02	7·85	7·74	8·18	8·16	7·55	9·50	8·69
	7·94	8·39	8·38	7·88	7·48	8·02	7·44	10·42	8·17
	7·91	8·36	8·05	7·46	7·66	7·81	7·43	9·47	7·51
	7·95	8·82	8·00	7·88	8·34	7·82	7·58	9·52	7·60
	7·92	8·41	7·91	8·28	8·77	8·14	7·74	8·76	7·80
Pepsin-HCl soluble protein	5·79	5·79	5·56	5·71	5·87	6·00	5·43	7·18	6·37
	5·90	5·98	5·99	5·63	5·37	5·81	5·25	7·54	5·93
	5·49	6·25	5·74	5·22	5·44	5·79	5·41	7·19	5·43
	5·69	6·39	5·78	5·74	5·92	5·81	5·28	7·00	5·47
	5·66	6·09	5·56	5·86	6·46	6·03	5·33	6·76	5·77
Ether extract	1·66	0·85	2·27	2·15	0·87	1·86	2·57	2·14	2·10
	1·42	1·74	1·74	2·76	0·87	1·73	2·38	1·80	1·51
	1·53	1·45	1·11	2·11	2·15	1·62	1·40	2·08	2·84
	0·95	1·59	1·63	1·42	2·46	1·65	1·64	1·92	2·28
	1·23	1·42	1·65	1·18	1·24	1·57	2·94	2·15	2·33
N-free extractives	53·41	51·56	51·05	53·36	53·23	54·84	53·84	51·86	52·82
	54·35	52·16	52·42	50 40	53·58	55·49	54·75	49·42	53·95
	53·17	51·83	52·59	52·10	52·91	54·22	53·55	49·66	51·58
	53·21	52·52	52·41	52·97	52·41	52·60	54·83	50·53	52·92
	54·23	53·68	53·90	53·90	53·29	54·09	53·71	51·42	52·14
Crude fibre	31·59	33·77	34·49	31·23	32·78	29·57	32·39	29·70	29·55
	31·58	32·91	32·92	32·97	33·02	29·75	32·57	31·05	30·92
	31·96	32·41	33·18	32·05	32·06	31·51	34·41	31·86	32·71
	31·91	31·63	33·79	31·45	31·78	31·58	32·71	31·21	31·68
	32·03	30·90	32·30	30·50	30·85	30·57	32·46	31·79	32·24
SiO_2-free ash	4·18	4·02	3·11	3·63	3·28	4·04	2·44	5·39	5·20
	3·58	3·05	3·64	4·20	3·73	3·66	1·71	5·81	3·91
	4·08	4·03	4·08	4·52	3·81	3·24	2·34	5·40	3·92
	4·28	3·80	2·88	4·39	3·43	4·38	2·39	5·11	3·66
	3·40	3·68	3·16	4·30	4·35	3·76	2·20	4·26	4·19
Lime (CaO)	0·475	0·443	0·193	0·535	0·330	0·579	0·134	0·821	0·631
	0·407	0·316	0·267	0·573	0·338	0·521	0·172	1·075	0·454
	0·426	0·423	0·330	0·615	0·371	0·408	0·073	0·823	0·325
	0·448	0·338	0·202	0·668	0·314	0·629	0·200	0·745	0·408
	0·381	0·420	0·322	0·804	0·400	0·501	0·110	0·480	0·410
Phosphoric acid (P_2O_5)	0·520	0·446	0·461	0·528	0·420	0·609	0·315	0·667	0·697
	0·456	0·384	0·386	0·610	0·380	0·539	0·256	0·735	0·608
	0·529	0·465	0·491	0·687	0·453	0·569	0·311	0·706	0·593
	0·579	0·385	0·410	0·695	0·334	0·794	0·294	0·725	0·552
	0·431	0·368	0·342	0·683	0·386	0·616	0·267	0·625	0·630

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INVESTIGATIONS ON YIELD IN CEREALS[1].

VIII. HYBRID VIGOUR IN WHEAT.

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(With Three Text-figures.)

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I. INTRODUCTION.

THE scientific interest of hybrid vigour, sometimes called "heterosis," is of long standing. In the extensive literature of the subject, not here to be reviewed, there are some unsatisfactory features. The most fundamental is inadequacy of the numerical evidence. Further, it is often impossible to tell exactly what is meant by "selfing": the pollen applied to a "selfed" plant may have been obtained from the plant itself or from another plant of the same "selfed" line.

During the past twenty years there has been a growing belief, with some evidence, that hybrid vigour might be exploited by plant breeders. In some crops, notably in maize and the tomato, crossed seed can be obtained in such quantity as to make it practicable to grow a commercial crop of F_1 plants. Substantial yield increases, by this means, have been claimed.

In breeding the naturally out-pollinating crop plants, the problem of hybrid vigour is inescapable and where, as in many of the commercial *Brassicae*, self-sterility is very high, the breeder is faced with peculiar difficulty. Out-pollinating plants, especially if highly self-sterile, are unfavourable material for study of the nature and causes of the phenomenon.

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[1] The earlier papers in this series have appeared in the *Journal of Agricultural Science*, **13**, **14** (3 parts), **15**, **16**, **18** (2 parts), **19** and **20**.

With the British cereals, which except rye are in most cases highly self-pollinating, there is some evidence for suspecting that hybrid vigour may be significant in breeding. This is especially so for wheat. Of the numerous wheat varieties produced by hybridisation, probably none has been wholly free from "splitting." That is, although when introduced into cultivation the new variety has seemed uniform, pure or fixed, rogues or off-type plants have, in the course of time, appeared (the demonstrable results of accidental admixture of seeds of other varieties are, of course, not under consideration). Only in a minority of cases has natural out-pollination been shown to account for the rogues: what part chromosome aberration or gene mutation has actually played in rogue production there is no evidence to decide. It has nevertheless seemed possible that the apparently uniform stock brought into cultivation has contained a substantial proportion of plants heterozygous in one or more factors but not discernibly different from the remaining and presumably wholly homozygous plants. Subsequent segregation might then, in time, produce a considerable number of plants visibly different from the rest. As a normal result of segregation the proportion of plants heterozygous in one or more factors would decrease with time. Theoretically, through this, the increasing loss of hybrid vigour might bring about a decline in the yield of commercial stocks. These speculations—for ignorance of the genetic basis of vigour and yield preclude firm evidence—bear on certain common beliefs. Many farmers hold that most new wheats of hybrid origin "run out" after some ten years or so. They allege that rogues appear and the yield declines. There is no sound evidence, and it is not difficult to think of non-genetic explanations of the belief. Thus the first growings of a new variety are often made by enterprising farmers who naturally desire to impress their neighbours by fine crops and sell them seed.

Although it would be impracticable to grow commercial crops of F_1 wheat plants, it might be possible, theoretically, assuming hybrid vigour is shown by this plant, to increase yields by regularly raising crops of, it may be, F_5 or F_6 plants. Upon consideration of all these circumstances it was decided to look for and study hybrid vigour in wheat. Comparisons of F_1 plants with the parents are limited in range by the difficulty of obtaining sufficient seed by crossing. It was therefore decided to work along two separate lines: first, to make an intensive study of one cross; concurrently to explore possibilities by comparing small F_0 and F_1 populations for a large range of crosses. In all cases plant development was studied by the easily determined but valuable index, rate of tiller formation, since an increase in "vigour" as judged by final yield of grain could not be interpreted without growth data.

Several different meanings have been attached to "vigour" by past observers. Yield of grain or of total dry matter, height of plant, earliness of maturation of seed, and resistance to disease have all been employed. For wheat, grain yield and tiller formation, known to be associated with it, have been considered the best measures of vigour and have been used in the investigations to be described. It is not to be inferred that this conception of vigour has any special biological claim. An acceptable general specification of vigour cannot yet be made and therefore in experimental work some arbitrary but clearly definable measure must be adopted.

A mathematical study of the possibility, explained above, that hybrid vigour may influence the yielding capacity of new hybrid wheat varieties has so far proved impracticable. Apart from the algebraic exercise involved, there is the great difficulty that the number and influence of the genes controlling yield or any other aspect of vigour are unknown.

Some experiments were also made on the embryo weight, respiration and other characteristics of F_1 grain, upon the influence of "bagging" ears when hybridising and upon other associated questions.

In naming the parents of a cross, in the passages which follow, the female is always written first.

II. THE EXPERIMENTAL WORK.

A statistical comparison of F_1, F_2 *and* F_3 *with the parent forms.*

Two varieties of wheat (both *T. vulgare*) were reciprocally crossed, viz. Little Joss (alternatively called Joss) and Thule. The former has red, smooth chaff, and the latter rough white so that accidental selfing during hybridising could easily be perceived in the F_1 populations. These wheats both grow well in Cambridge and flower at about the same time, so that crossing is relatively simple and well-developed F_1 populations may be relied upon. The growings were:

Generation	Year	Plot lay-out
The reciprocal F_1's and both parents	1929–30	A 4 × 4 Latin Square with 108 seeds per plot
F_2 and both parents (the F_2 was from an equal mixture of the seeds set by the reciprocal F_1's)	1930–1	A 4 × 4 Latin Square with 560 seeds per plot. The Latin Square was sown in duplicate
F_1's and both parents F_2's and both parents F_3's and both parents	1931–2	In each case a 4 × 4 Latin Square with 162 seeds per plot

In the plots the sowing interval was 8 × 2 in.

Small-scale observational comparisons of the F_1 *and the parents for a large range of crosses.*

The F_1 population was of about twenty-five plants only, so that although actual measures of germination, tillering and yield were made the data cannot be examined statistically. It was hoped that these experiments might reveal some cases of marked hybrid vigour and show the relative value of parental forms in relation to the phenomenon. The crosses were in four groups, viz.:

Between varieties of *T. vulgare* (21 chromosomes).
Between the 14 chromosome species.
Between the 21 chromosome species.
Between the 14 and 21 chromosome species.

In almost all cases reciprocal crosses were made. There were also made nine inter-varietal and eleven inter-species crosses with barley.

Physiological experiments.

Comparisons of F_1 and the parents were made in:

Embryo weight.
Rate of dry weight increase.
Rate of respiration of germinating grains.

The respiration experiments were carried out by Dr H. R. Barnell in the Botany School, Cambridge, to whom we are much indebted.

The effect upon grain development and germination of covering the ear with a waterproof paper bag during hybridising was also studied. Further, the act of hybridising has often (especially by seedsmen) been alleged to have an important influence on vigour when plants of the same wheat variety are used as parents. This matter was investigated.

III. A DETAILED STUDY OF THE CROSS LITTLE JOSS × THULE.

Reciprocal crosses were made between these two varieties and the F_1, F_2 and F_3 generations were compared with the parents in the manner explained in section II (*supra*). In 1931–2 there were daily counts of germination and of rate of leaf formation. In this, and in the other two crop-years also, some observations on tillering and determinations of final yield of grain were carried out.

(*a*) *Germination.* Fig. 1 displays the results. The initial differences between the parents themselves and between the two (reciprocal) F_1's are not significant. But at every germination count shown in the figure the F_1 values are significantly greater than those for either parent, in most cases at the 100 : 1 point and in all at the 20 : 1 point at least.

(*b*) *Leaf formation.* In the common winter wheats, as grown in Cambridge, the first side tiller usually appears with or shortly after the fourth leaf on the main axis. The rate at which the first four leaves become visible is a fairly well defined varietal characteristic. Counts made in 1931–2 showed the F_1 populations to be in advance of both parents in rate of leaf formation (prior to the commencement of tillering). The F_2 from Joss × Thule had significantly more leaves than either parent, but the reciprocal F_2 exceeded only the Thule parent. Both the F_3 generations were significantly greater than Thule but not significantly greater than Joss.

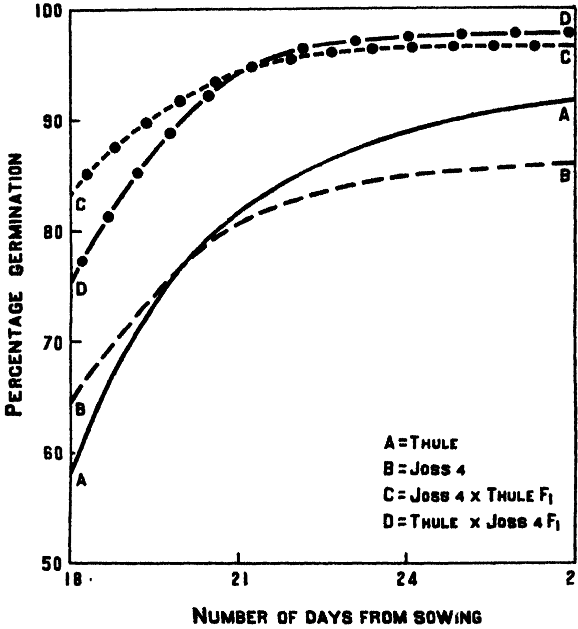

Fig. 1. Illustrating differences in rate and amount of germination in hybrids and their parents. (F_1 data, autumn 1931.)

(*c*) *Tillering*, taken to mean number of side shoots (*i.e.* additional to the main axis of the plant), gave results which, for all the counts made, are shown fully in Table I. The essential differences are set out below where T = Thule, J = Little Joss, J × T = F_x Joss × Thule, T × J = F_x Thule × Joss, > = significantly greater at the 100 : 1 point, and (>) = significantly greater between the 20 : 1 and 100 : 1 points. It will be seen that many actual differences in Table I were not statistically significant but in some cases, for instance, the difference between the reciprocal F_1's in 1929–30, the constancy of sign of the difference deserves to be noticed.

F_1 J × T > T at 6 out of 6 counts in 1929–30
> T ,, 1 ,, 1 ,, 1931–32
> J ,, 2 ,, 6 ,, 1929–30
> J ,, 1 ,, 1 ,, 1931–32
> F_1 T × J ,, 2 ,, 6 ,, 1929–30
> F_1 T × J ,, 1 ,, 1 ,, 1931–32

F_1 T × J > T at 6 out of 6 counts in 1929–30
> T ,, 1 ,, 1 ,, 1931–32
< J ,, 2 ,, 6 ,, 1929–30
> J ,, 1 ,, 1 ,, 1931–32
< F_1 J × T ,, 2 ,, 6 ,, 1929–30
< F_1 J × T ,, 1 ,, 1 ,, 1931–32

F_2 J × T > T at 4 out of 4 counts in 1930–31
> T ,, 1 ,, 1 ,, 1931–32
< J ,, 4 ,, 4 ,, 1930–31
< J ,, 0 ,, 1 ,, 1931–32
> F_2 T × J ,, 1 ,, 4 ,, 1930–31
(>) F_2 T × J ,, 1 ,, 1 ,, 1931–32

F_2 T × J > T at 4 out of 4 counts in 1930–31
> T ,, 1 ,, 1 ,, 1931–32
< J ,, 4 ,, 4 ,, 1930–31
< J ,, 1 ,, 1 ,, 1931–32
(<) F_2 J × T ,, 1 ,, 4 ,, 1930–31
(<) F_2 J × T ,, 1 ,, 1 ,, 1931–32

F_3 J × T > T at 1 out of 1 count in 1931–32
< J ,, 1 ,, 1 ,, ,,
> F_3 T × J ,, 0 ,, 1 ,, ,,

F_3 T × J > T at 1 out of 1 count in 1931–32
< J ,, 1 ,, 1 ,, ,,
< F_3 J × T ,, 0 ,, 1 ,, ,,

For the parents we find J > T at all the thirteen counts in the three years combined, and significantly so in eleven of them.

(*d*) *Yield*, in the form of weight of grain per unit area, is given in Table II. Although in sowing the spacing was the same in all plots, an acceptable measure of average yield per plant cannot be obtained, for mortality, and, therefore, effective spacing, was not the same in all four populations (two parents and two (reciprocal) hybrids).

Employing the same notation as for (*c*) Tillering (*supra*) the significant differences are:

F_1 J × T > T in 1931–32
> J ,, ,,
F_1 T × J > T in 1931–32
> J ,, ,,
F_2 J × T > T in 1931–32
F_2 T × J > T in 1931–32
F_3 No differences significant
J > T in 1931–32 (in the comparisons of F_1 and F_2 but not of F_3)

In most of the previously published experiments on hybrid vigour the data do not allow of comparison between season and season. There is a noteworthy exception in Bredeman and Heuser (1931) who, in a comprehensive six-year experiment with rye, were so impressed by differences in "vigour" from year to year that they spoke of good and bad "heterosis years." Table I and II show that for F_1 in 1929–30, Joss × Thule exceeded both parents and its reciprocal in tillering and one parent in yield, the reciprocal being intermediate between the parents. In 1931–2, however, the F_1's for both directions of the cross exceeded both the parents in

Table I. *Average number of side tillers per plant* (i.e. *not counting the main axis*) *in Joss, Thule, and their* F_1, F_2 *and* F_3 *generations. The numbers are expressed on the basis of the general mean* (*of the two parents and the two hybrid generations*) = 100.

Date of count	Joss	Thule	Joss × Thule	Thule × Joss
	F_1 1929–30.			
25. i.	113·4	56·7	119·8	111·5
1. ii.	111·1	66·8	116·6	107·5
15. ii.	114·1	64·2	116·5	105·0
1. iii.	109·9	63·2	120·2	106·5
15. iii.	109·5	70·9	114·3	105·3
8. viii. (harvest)	109·1	92·9	101·0	97·0
	F_1 1931–2.			
23. ii.	92·5	64·3	123·4	119·7
	F_2 1930–1.			
27. i.	148·4	34·4	123·0	95·1
17. ii.	120·7	77·5	102·4	100·0
18. iii.	135·4	67·0	99·7	98·3
16. iv.	113·4	82·3	104·4	99·7
	F_2 1931–2.			
25. ii.	115·7	71·8	110·9	101·7
	F_3 1931–2.			
26. ii.	121·1	75·5	103·7	99·9

Table II. *Yield of grain* (*air-dry*) *per unit area of Joss, Thule, and their* F_1, F_2 *and* F_3 *generations. The yields are expressed on the basis of the general mean* (*of the two parents and the two hybrid generations*) = 100.

Year	Joss	Thule	Joss × Thule	Thule × Joss
	F_1			
1929–30	103·9	88·3 ✓	104·0 ✓	103·7
1931–2	97·5 -	83·8 -	111·3 ✓+	107·4 +
	F_2			
1930–1	106·6	98·3	94·6	100·0
Duplicate sowing	106·6	95·1	97·7	100·7
1931–2	110·1	81·6	104·1	104·3
	F_3			
1931–2	110·7	95·6	98·9	96·1

tillering and also in yield. The facts do not, however, afford any support to the "heterosis year" idea: they may be attributed to the ordinary seasonal fluctuations always met in comparisons between varieties.

IV. COMPARATIVE VIGOUR OF THE F_1, F_2 AND F_3 GENERATIONS, AND OF THE RECIPROCAL DIRECTIONS, OF THE CROSS LITTLE JOSS × THULE.

It is evident that in this wheat cross there are none of the marked differences which in certain crosses in maize and other crops make hybrid vigour a striking phenomenon. Comparisons of hybrid generations by means of the data of section III suggest, however, that an effect of the same nature as hybrid vigour is discernible in this cross.

For convenience, the reciprocal directions of the cross will be compared first. In the F_1 generation no differences were found for germination and early leaf formation. Constant observation gave rise to the impression that F_1 J × T was growing, and in particular tillering, far more vigorously than its reciprocal. Periodic counts showed, however, that the tillering difference was significant on only three out of seven occasions in the 1929–30 and 1931–2 crops combined. As Table I shows, the difference had on all seven occasions the same sign, and since the plots were only four times replicated it may be inferred that the one direction of the cross showed in F_1 a small but certain increase in vigour of tillering over the other direction. This difference, however, was not followed up by a difference in yield for unit area. For the F_2 generation (*cf.* section III (*supra*)) there is slight evidence for the superior early leaf formation and tillering of J × T as compared with T × J but no yield difference between them. The reciprocal F_3's show no significant differences at all.

Taking the F_1, F_2 and F_3 generations together, it is seen that reciprocal differences are fairly common but never large. But it is important to observe that every significant difference is in the same direction, viz. J × T > T × J. Observations made by eye all through the growing period gave rise to the impression that this directional superiority was well marked though far more apparent in the first five or six months than in later life. Any farmer would have said, especially of the F_1's, that J × T was "more vigorous" than T × J. It is probable that there is here a genuine reciprocal difference of some kind, but to identify it comparisons will have to be made on a much larger scale. The chief difficulty of this will naturally be the production of very large numbers of crossed seeds.

The relative "vigour" of the successive generations may now be compared. For germination the data is only for the parents and F_1's. In respect of early leaf formation (*cf.* section III (*supra*)) there is evidence of a steady decline. Thus both (reciprocal) F_1's exceed both parents; one F_2 exceeds both parents and the reciprocal exceeds only one parent; both F_3's exceed only one of the parents. Very similar situations occur in both tillering and yield. While the data cannot be pressed to a critical analysis it clearly suggests that the order of vigour (measured by early leaf formation, tillering, and yield) is $F_0 < F_1 > F_2 > F_3$.

This comparison of successive hybrid generations bears upon certain of the suggested explanations of the causes of "hybrid vigour." It can be argued that hybrid vigour is in no way dependent on any "stimulus of hybridity" but simply results from the interaction of complementary genes favourable to vigorous growth. Thus the F_1, combining the genes of both parents will, in a favourable case, be more vigorous than the parents. In F_2 segregation will occur, and the various phenotypes resulting will display various degrees of vigour. Some will equal or perhaps exceed the F_1; others will fall short of the less vigorous of the F_0 (parent) forms. Therefore the frequency distribution of vigour for the F_2 generation as a whole is likely to be skew or asymmetrical. In reference to this point the frequency distribution of number of side tillers per plant—one of the measures of vigour here adopted—has been set out in Fig. 2 for the F_1 (1931–2), F_2 and F_3 of Little Joss × Thule. The F_2 and F_3 distributions are not by any means noticeably skew. The F_2 of 1930–1 totalling 8960 plants gave a distribution closely similar to that shown in Fig. 3. Improved tests for skewness have recently been devised, but it is not worth while to

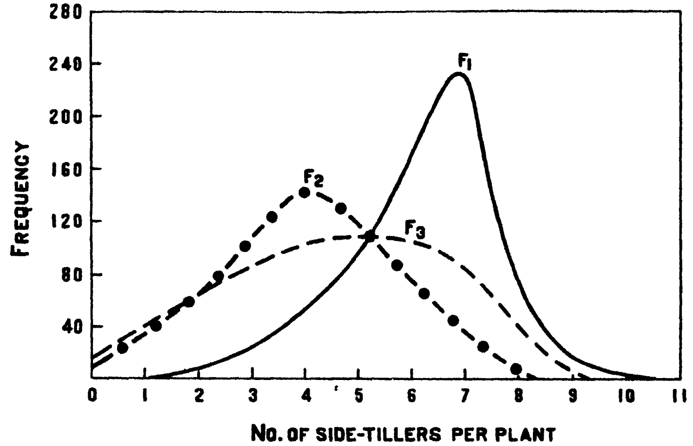

Fig. 2. Illustrating frequency distribution in F_1, F_2 and F_3, of number of tillers per plant during the last week of February, 1932.

apply these to the present case in which skewness is evidently, at the most, no more than very slight. To demonstrate a slight skewness in the F_2 distribution would do no more than suggest segregation of genes affecting tillering. Some such segregation can hardly be conceived not to occur. But unless the genes had a marked influence on tillering they could not be held to account for great vigour (of tillering) in the F_1. Merely to demonstrate their occurrence would not be at all the same as the much more difficult task of measuring their effect. This latter fact is often ignored in attempts to explain "hybrid vigour" as the direct result of complementary genes. That reciprocal F_1's differ is a further reason against a factorial explanation of hybrid vigour whether single "complementary factors" or "dominant growth factors" be postulated.

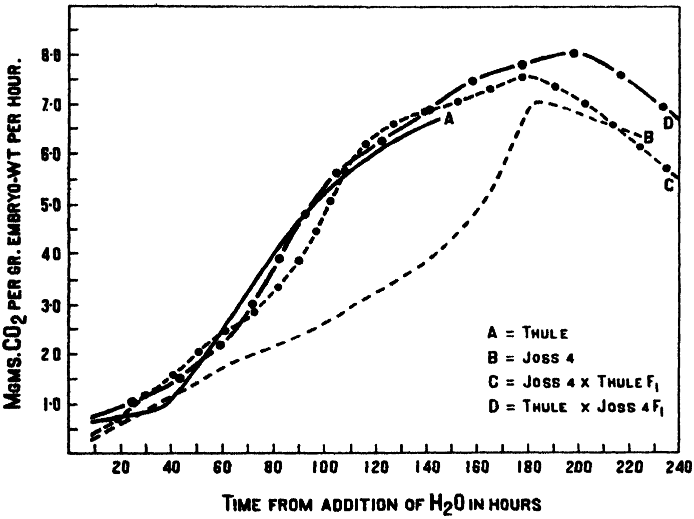

Fig. 3. Illustrating relative respiration of growing embryos of hybrids and their parents.

V. Observations on a wide range of crosses; various phenomena connected with hybridity.

The exploratory purpose of a wide range of crosses, each on a scale not large enough for strict statistical examination, has been explained in section II (*supra*). There is a full list of the parents used in the crosses in (4) of the present section. The main trends of the result will be given in spite of the limitation of statistically low numbers of observations. For, on the one hand, it is difficult to make really adequate numbers of crosses:

and on the other, one of the chief clues to the nature of the obscure phenomenon of hybrid vigour is to settle its range of occurrence.

(1) *Crossability.*

In hybridising wheats there has arisen a general impression that, even among closely related forms having the same chromosome number, it is easier to cross some varieties than others. Moreover, a larger proportion of hybrid grains to florets pollinated may in some cases be obtained in one direction of a cross than in the other.

In the cases here studied the proportion of successful pollinations (number of grains set to number of florets pollinated) was in several as high when distantly related (different species) forms with the same chromosome number were crossed as in intervarietal (same species) crosses.

It was found, too, that some varieties seemed to have an optimum period for crossing. For instance in the Joss × Thule cross one and the same investigator (B. P. P.) hybridised 56 ears (using 24 florets per ear for the F_0 ♀) between June 20th and 29th. The results were:

Joss × Thule		Thule × Joss	
Date of pollination (June)	% of seeds set	Date of pollination (June)	% of seeds set
20	29	—	—
21	82	21	83
22	73	22	87
26	61	23	65
27	79	26	54
29	31	29	58

Many factors affect the success of pollination and to demonstrate completely the occurrence of an optimum period would require detailed experiment and make it necessary to measure the influence of several meteorological factors. It can be said, for this experiment at any rate, that whenever pollinations were made there was abundance of pollen available.

In crosses where the parents mature their anthers at considerably different times, differences in crossability between the reciprocal directions may, perhaps, be simply explained. But the three wheats Yeoman (*T. vulgare*), Red Fife (*T. vulgare*) and White Spelt (*T. spelta*), in crosses where no doubt was occasioned by time of anther maturation, always proved more successful as female than as male parents.

(2) *Xenia* (*grain weight effects*).

In wheat, the previously published evidence of xenia effects is conflicting, and comparison between weight of the crossed grain and weight of the grain of the parents seems to have been restricted to the female parent. Table III gives the results from the crosses now under discussion. Their trend suggests that in inter-varietal (*T. vulgare*) crosses, the crossed grain is usually heavier than that of one or other of the parents and often heavier than both. In the other categories of crosses there is a general tendency to decrease below the parental values.

Table III. *The relative weight of the crossed grain and of the grains of the parent forms. A cross and its reciprocal are separately entered. The crosses were made in* 1932. *The upper line of each entry in the table gives the number of crosses concerned, the lower (in brackets) the limits of the increase per cent. over the stated or the larger grained parent* (F_0) *or of the decrease per cent. below the smaller grained parent.*

	Crosses between hexaploid wheats (all *T. vulgare*)	Interspecies crosses of tetraploid wheats	Interspecies crosses of hexaploid wheats	Interspecies crosses of tetraploid and hexaploid wheats
Decrease below both F_0's	6 (1–35)	9 (2–47)	4 (8–23)	3 (14–58)
Increase over F_0 ♂ but not over F_0 ♀	4 (13–49)	5 (8–20)	7 (1–73)	Nil
Increase over F_0 ♀ but not over F_0 ♂	11 (2–46)	2 (2–18)	3 (3–36)	Nil
Increase over both F_0's	13 (1–24)	2 (1–2)	3 (4–21)	Nil
Total crosses made	34	18	17	3

Examination of the results suggests that the occurrence of crossed grains of weight greater than the parental grains is not correlated with the grain size of the male parent. This is in agreement with Collins and Kempton (1913) but the data are not sufficient to cast doubt on Kakizaki (1931) who says "it must be concluded that" (in the egg plant) "the increase in weight of the F_1 seed has a tendency to be influenced positively by the weight of the seed of the pollen parent but the tendency is not great."

Wolfe (1915), for maize, named two varieties which gave decreased grain weight in a larger proportion of their crosses than any of the other varieties he employed. One of the wheats here used, Tom Thumb (*T. vulgare*), produced characteristically shrivelled grain. The grains it set when pollinated with strongly growing English varieties of *T. vulgare* were invariably shrivelled and poorly filled. In contrast the *T. vulgare* forms Chinese White and Iron gave, in all the crosses in which they were the female parent, excellently filled grain.

(3) *Tillering and yield of* F_1 *and* F_0.

Actual counts were made as checks upon eye-impressions. They cannot be used here because of the smallness of the plant populations concerned. The general conclusion is that most of the F_1's tillered more profusely than their parents, the difference being in some crosses very striking indeed. Some of these outstanding cases will be studied on a large scale. In yield, there appeared also to be differences harmonious with those in tillering. The cross, Little Joss × Yeoman, was in two seasons apparently an outstanding example of hybrid vigour in F_1.

(4) *The influence of certain varieties when used as parents.*

The parents used for this series of crosses were:

Tetraploid	Hexaploid
Emmer (*T. dicoccum*)	White Spelt (*T. spelta*)
Persian Black (*T. persicum*)	American Club (*T. compactum*)
Kubanka (*T. durum*)	Sphaerococcum (*T. Sphaerococcum*)
Polish (*T. polonicum*)	Red Fife (*T. vulgare*)
Rivet (*T. turgidum*)	Squarehead's Master (*T. vulgare*)
	Little Joss (*T. vulgare*)
	Yeoman (*T. vulgare*)
	Red Marvel (*T. vulgare*)
	Hen Gymro (*T. vulgare*)
	Old Fashioned 2 (*T. vulgare*)
	Tom Thumb (*T. vulgare*)
	Victor (*T. vulgare*)
	Iron (*T. vulgare*)
	Thule (*T. vulgare*)
	Chinese White (*T. vulgare*)

In most cases the cross was made reciprocally and counting a cross and its reciprocal separately the number of crosses was:

T. vulgare × *T. vulgare* – 56.
Hexaploid species × Hexaploid species – 17.
Tetraploid species × Tetraploid species – 18.
Hexaploid species × Tetraploid species – 3.

From eye observation, checked by tiller counts (not amenable to statistical examination), it was concluded that some of the varieties influenced their F_1 progeny in characteristic ways. The outstanding examples occurred in the *T. vulgare* × *T. vulgare* crosses. Red Marvel, Iron and Old Fashioned 2, whether used as male or female parents, gave in all their crosses F_1's of markedly lower tillering capacity than the higher tillering of the two parents. Tom Thumb, as a female parent, always gave poor F_1's: as male parent it gave very vigorous progeny. The outstanding variety was Chinese White, its F_1's being always very vigorous (for tillering) whether it was used as male or female parent. It was the only variety which produced anything but an inferior F_1 in crosses with Red Marvel (which gave poor results even with such thriving varieties as Iron and Little Joss). This is the more noteworthy from the fact that Chinese White itself does not tiller vigorously in comparison with most of the *T. vulgare* forms employed. (It was concluded that no general connection subsisted between vigour of tillering of the parent varieties and of the resulting F_1.) Rivet wheat in tetraploid × tetraploid almost invariably gave good issue as a female parent while Polish stood out as a male parent. In hexaploid inter-species crosses White Spelt gave markedly good F_1's in both directions and *T. sphaerococcum* in most, but not all cases, very poor ones. These results reinforce the view of some other investigators (*e.g.* Jenkins' (1929)) that some varieties characteristically give vigorous and others feeble F_1's. Taken with the additional conclusion that some varieties give much better F_1's in one direction than in the reciprocal direction of a cross, it opens an approach, albeit lengthy, to the nature and causes of hybrid vigour.

(5) *Barley crosses.*

All cultivated barleys (*H. sativum*) are diploid. Several crosses were made using both six-row (*H.s. hexastichum*) and 2-row (*H.s. distichum*) forms. Only a few instances of apparent hybrid vigour in F_1 were found and these not so marked as in wheat. In all cases the weight of the crossed grain was less than that of the lighter-grained parent.

VI. PHYSIOLOGICAL ASPECTS.

The studies made by Ashby (1930, 1932) on maize seem to stand almost alone as an endeavour to deal with the physiological aspects of hybrid vigour. He argued that the hybrid vigour of the F_1 between two inbred lines of maize might arise from (i) larger cells (somatic) in the tissues of the F_1, (ii) more meristematic centres in the F_1 with, consequently, the formation of more leaves and tillers, (iii) greater photo-synthetic efficiency, (iv) the falling off of the sigmoid growth curve occurring later in the season for the F_1 than for the parents. Ashby concluded that (*a*) "the only physiological differences observed were an increased percentage germination on the part of the hybrid, and also a greater initial weight of the embryo, which gave an advantage which was maintained throughout the grand period of growth," (*b*) "the hybrid does not differ in the least from its more vigorous parent as regards relative growth rate."

(1) *Embryo weight.*

This was studied in the Joss × Thule cross, using ten grains from each parent and from each of the reciprocal directions of the cross; and also in the Joss and Yeoman cross, using 120 grains (12 lots each of 10) of each of the four categories. The latter cross, though not studied in full like the former, appeared to give an exceptionally vigorous F_1. The seeds were placed on layers of filter paper in Petri dishes, just covered with distilled water, and kept for 24 hours in an incubator at 23° C. Upon removal the grains were dried (surface moisture) with filter paper, and weighed. Then the embryos were dissected out and weighed (=fresh weight of embryo) and finally, after 24 hours in an oven at about 100° C., they were again weighed (=dry weight of embryo). No effect corresponding to that recorded for maize by Ashby was found. The dry weight of the embryo was the same for crossed grains formed on Thule plants pollinated by Joss as for grains formed on Thule by normal selfing. A corresponding result was obtained with Joss as the female parent in this cross. The more numerous observations on the Joss × Yeoman cross led to the same conclusion.

(2) *The effect of "artificial selfing."*

Practical breeders and seed producers have often affirmed that the act of artificial pollination confers on the resulting seed an extra "vigour of growth" even when the parent plants belong to the same pure line. Thus seed of a pure line of wheat obtained by artificially inter-crossing plants of that line should, and is alleged to, give more vigorous plants and higher yield than seed of the same line resulting from normal selfing. The practical significance of this idea is not now in question, but it is necessary to find out whether the technique of crossing does, in experiments on hybrid vigour, favour in any way either the selfed grain of the parents or the crossed grain. Both naturally and artificially selfed seed of six wheat varieties was obtained under the same growing conditions for all. Tests showed that, for five of the varieties, the artificially selfed seed germinated more rapidly in soil than the naturally selfed. At the end of 40 days from sowing, however, the total germinations were in all six varieties the same for both kinds of selfed seed. In another series of experiments it was shown that embryo dry weight was also the same in artificially and naturally selfed seed. Artificial selfing was carried out in exactly the same way as artificial crossing (save for the kind of pollen used). The ear of the female parent plant was thus enclosed in the usual grease-proof paper bag after emasculation. It was decided to find out whether the use of the paper bag (ordinarily left on till the seed is mature) had any effect on grain size or germination capacity. A suitable number of ears on a plot was bagged and the remainder left untouched. Comparison was then made between the "bagged" and "unbagged" grains (both being the result of selfing). No difference in germination or in any other respect was, however, found. It seems, therefore, that the crossing technique ordinarily employed for wheat is acceptable in investigations on hybrid vigour.

(3) *Respiration rates of germinating grains, hybrid and parental.*

Dr H. R. Barnell (then working in the Botany School, Cambridge) very kindly made measurements of respiration of germinating grains by the Pettenkofer method. He used the parental and reciprocal crossed grains of the Joss × Thule cross which, as described in sections III and IV (*supra*), showed a small but securely demonstrated degree of "hybrid vigour" in F_1. It was possible to provide only ten grains of each of the hybrid kinds: Fig. 3 gives his results. In conformity with Lyon (1928) the respiration of the embryo has been assumed (in Fig. 3) to be one-sixth of that of the complete grain. The validity of this is not here important since, of course, the relative values for the four categories of grain remain unaffected. Minor features of the curves in Fig. 3 cannot be stressed. It may be inferred, however, that up to 180 hours from the time of putting the grains in water the more vigorous parent, Joss, has a decidedly lower respiration than Thule: and further, that both kinds of crossed grain respire at about the same rate as Thule. Experiments were also made on rate of dry-weight increase of the growing embryo. The results were not in harmony with either the respiration results or with the idea that hybrid vigour in wheat is controlled, as Ashby concluded it to be in maize, by initial embryo weight.

The weakness of the work described in this paragraph lies in paucity of data. It is a heavy task to produce sufficient crossed grains for replicated plots on which to measure germination, tillering and yield and also grains for embryo weight and respiration studies. Ashby had to rely on even smaller numbers but, in the conclusion that the embryo of the crossed grain of maize is heavier than the parental, he could claim independent support from East and Jones (1920) and other writers on maize, although Jones (1918) might perhaps be set up in opposition (he found F_2 plants from large seeds set by F_1 were larger at first than F_1 plants from poor seed set by inbred parents: in later growth, however, this difference was reversed). Several other published results bearing on this point might be adduced. In substance relevant, they are not, however, soundly established by statistical proof. It must be concluded that while in maize hybrid vigour appears to be associated with embryo weight, in wheat the absence of such an association seems probable. Very much more extensive experiments than any so far made will be needed to follow up this interesting possible clue to the nature of hybrid vigour.

In section IV it was explained that the superior vigour of F_1, in comparison with the parents, was most evident in early growth, becoming less in later life. To the eye this decline was very impressive in many of the crosses. It strikingly resembled the early "stimulus" observed to result from some "seed dressings" (fungicidal) used for cereals which also loses its effect long before the plants reach maturity. It seems not unreasonable to suggest therefore that hybrid vigour, as a phenomenon of juvenile life is, at any rate in part, of the nature of a temporary stimulus set up by the act, or consequences, of causing unlike gametes to unite.

(4) *Some general inferences.*

An examination has been made of the whole of the literature bearing upon hybrid vigour. There has been assembled a list of all the crosses in which the phenomenon appears to have been clearly shown. Admissibility of evidence has had to be determined from the recorded circumstances, for the cases are few indeed in which trustworthy numerical evidence is given. Of the apparently sound cases fourteen are for crosses among varieties of the same species, the species involved being: *Zea Mays*, *Z. saccharata*, *Andropogon sorghum*, *Secale cereale*, *Solanum melongena*, *Lycopersicum esculentum*, *Petunia violacea*, *Digitalis purpurea*, *Mimulus luteus*, *Viola tricolor*, *Dianthus caryophyllus*, *Nemophila insignis*, *Brassica oleracea*, *Soja max*.

Of interspecies crosses in which hybrid vigour seems to have been shown clearly there are twenty-nine cases involving two or more species of the following genera: *Solanum*, *Datura*, *Petunia*, *Lycium*, *Nicotiana*, *Verbascum*, *Digitalis*, *Pentstemon*, *Malva*, *Althaea*, *Lavatera*, *Tropaeolum*, *Cucumis*, *Lobelia*, *Mirabilis*.

So far as this select list goes there is evidence that hybrid vigour occurs preponderantly in crosses among parents which are (*a*) diploid, (*b*) naturally out-pollinating and (*c*) endospermic in seed. In a paper on polyploidy in *Prunus* Darlington (1928) observed "the most striking results in hybrid vigour are obtained by crossing diploids and not polyploids." The few exceptions to the diploidy-vigour association for the cases here considered occur in some of the crosses of *Solanum*, *Digitalis* and *Nicotiana*. In the matter of cross-fertilisation Watkins (1932) has expressed the view that "cross-fertilised species such as *Nicotiana* and *Crepis* may be expected to show hybrid vigour." The only exceptions to this association with the habit of cross-fertilisation found in the cases under discussion were *Soja max*, *Phaseolus vulgaris* and *Lycopersicum esculentum*. The significance of the association of diploidy, out-pollination and endospermic seed with hybrid vigour cannot yet be judged. It is highly probable that many varieties and species so far not observed show considerable hybrid vigour. Moreover it remains to find out whether the frequency of occurrence of these three characteristics in plants showing hybrid vigour is greatly in excess of their frequency in flowering plants at large.

VII. SUMMARY.

Of the genetic problems upon the solution of which immediate progress in plant breeding depends, hybrid vigour is in the front rank. This is particularly the case in naturally out-pollinating and highly self-sterile plants such as many forms of *Brassica oleracea*, and some of the pasture plants. But in these, genetic experiment is peculiarly difficult. With some crops, notably maize and the tomato, it has proved practicable and clearly advantageous to grow commercial crops of F_1 plants. Even in the British cereals (all, save rye, highly self-fertile and self-pollinating) there are grounds for believing hybrid vigour to be of some economic interest. A thorough investigation of vigour was therefore made in the cross Little Joss × Thule (both *T. vulgare*) in the F_1, F_2 and F_3 generations. In addition a range of ninety-four crosses was studied on a small scale. Of these fifty-six were between varieties of *T. vulgare*, the remainder being interspecies, some with parents of the same chromosome number and some not. "Vigour," variably specified by investigators, was here taken to be yield of grain together with the associated attribute, tillering. Certain physiological experiments were also made on grain weight, germination rate, embryo weight and respiration rate of the germinating grain. The crosses were made reciprocally.

The cross Little Joss × Thule, while not showing the striking effects that have made hybrid vigour notable in maize, clearly displayed the phenomenon. Between the reciprocal directions of the cross, small but statistically certain differences were established in F_1; in F_2 there were slight indications of difference; the F_3's were identical in vigour. These reciprocal differences make a factorial explanation of hybrid vigour (whether resting simply on complementary factors or on dominant growth factors) difficult to accept.

Vigour in the successive hybrid generations, as compared with the parents (F_0), was clearly in the order $F_0 < F_1 > F_2 > F_3$. The F_2 frequency distribution of number of tillers per plant was not markedly skew—a further evidence against the factorial explanation of hybrid vigour.

From the wide range of crosses a number of general inferences was drawn: (i) In some varieties a restricted optimum period for crossing was found. (ii) Certain wheats regularly proved more successful (proportion of successful pollinations) as female than as male parents. (iii) In crosses of *T. vulgare* by *T. vulgare*, the actual crossed grain was in most cases of greater weight than that of one parent and often heavier than either. With interspecies crosses, however, even when the parents had the same chromosome number, decrease instead of increase was found in most cases. (iv) An F_1 of greater tillering capacity and yield than its parents resulted from most of the crosses. (v) But there were important exceptions, and certain varieties stood out as good or bad, in respect of vigour of F_1 progeny, when used as male parent or female, or in both directions of crossing. This fact opens an approach, though lengthy, to the causes of hybrid vigour.

From the physiological experiments it was clear that Ashby's explanation of hybrid vigour in maize F_1's as resulting solely from the greater embryo weight of the crossed grain, was inapplicable to wheat. No increase over parental embryo weight occurred. The crossing technique ordinarily used with wheat was shown not to affect the vigour of growth of the resulting grain, *i.e.* to have no effect save that resulting from the particular kind of pollen used. Measurements of respiration rate of germinating grains gave further evidence against the possibility that embryo weight influences hybrid vigour in wheat. It appears possible that an enhanced vigour in early life, not carried on into maturity, is occasioned by some stimulus arising from the union of dissimilar gametes.

From examination of all the published cases of hybrid vigour it appears that the phenomenon occurs preponderantly in crosses among parents which are (*a*) diploid, (*b*) naturally out-pollinating and (*c*) endospermic in seed.

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NOTE ON THE VITAMIN B_1 POTENCY OF WHEAT AS INFLUENCED BY SOIL TREATMENT.

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(With Four Text-figures.)

McCarrison and Viswanath (1926) claimed that wheat grown on soil treated with cattle manure was 15 per cent. richer in vitamin B than was that from land treated with chemical fertiliser. On the other hand Hunt (1927) concluded that acid phosphate produced wheat with the highest vitamin B content. Rowlands and Wilkinson (1930) found that grass seed from land manured with pig dung (which was rich in vitamin B), was more active than grass seed from land treated with artificial manure.

The purpose of the present note is to describe the results of a comparison carried out at the Nutritional Laboratory, Cambridge, of the vitamin B_1 activities of specimens of wheat grain grown on various experimental plots at the Rothamsted Experimental Station. The varied nature of the soil treatment received by the different specimens is indicated by the following particulars:

No. of plot	
3	No manure
2 B	14 tons of dung per acre
5	Complete mineral manure
7	Complete mineral manure + 412 lb. of sulphate of ammonia per acre
10	412 lb. of sulphate of ammonia only per acre

Our results indicate that there was a somewhat larger amount of vitamin B_1 in the specimens of wholemeal wheat flour from the plots which had been treated with ammonium sulphate. The difference, however, is not of a striking order.

Experimental.

Attempts were first made to compare the vitamin B_1 value of the wholemeal flours by the standard technique of growth tests on rats. This method was found inapplicable, however, as the majority of our animals spontaneously became refected. Tests based on cure of head retractions in pigeons presented the difficulty of feeding the sufficiently large doses

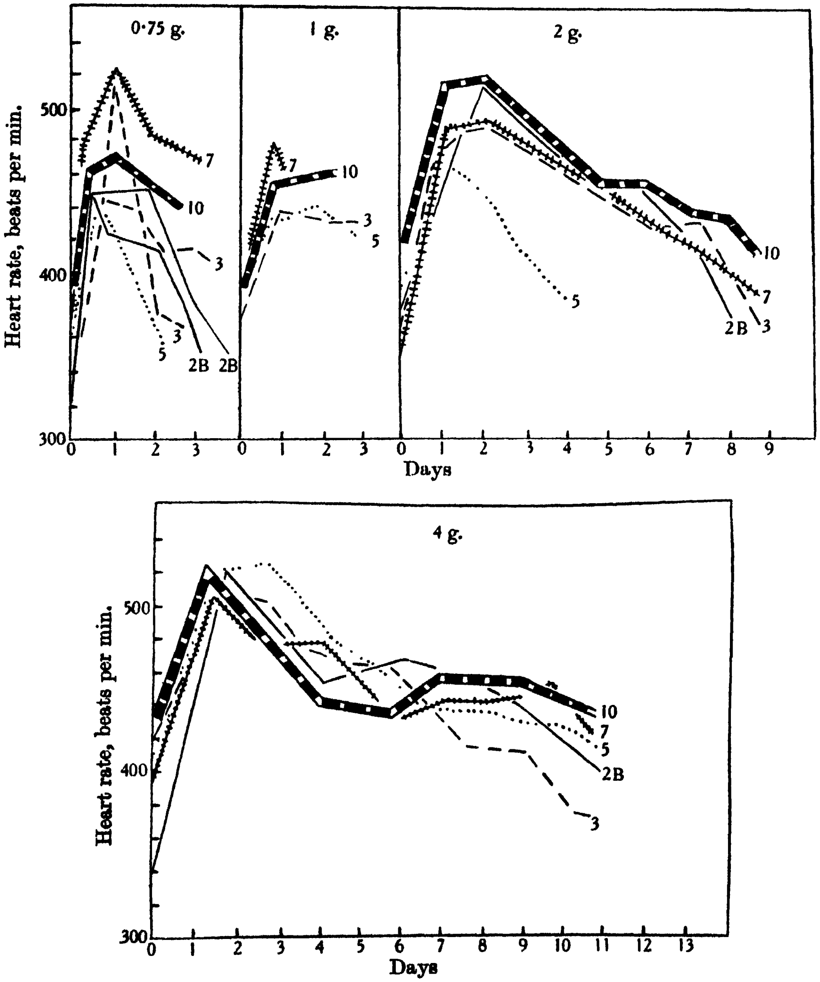

Fig. 1. Heart rate following administration of single dose of whole wheat. Comparison of effect at four graded levels.

———— = Plot 2 B — — — = Plot 3 ······ = Plot 5
++++++ = „ 7 ▬▭▬ = „ 10

of wholemeal flour which would be needed. Recourse was therefore had to the heart-rate method (Drury, Harris and Maudsley, 1930; Birch and Harris, 1934). The shortness of the time taken for this test rules out any risk of refection.

RESULTS BY THE HEART-RATE METHOD.

In preliminary orientation experiments graded doses of the four specimens of wholemeal were fed (Fig. 1). The results indicated that the level of 2 gm. is a suitable dose for carrying out the more detailed

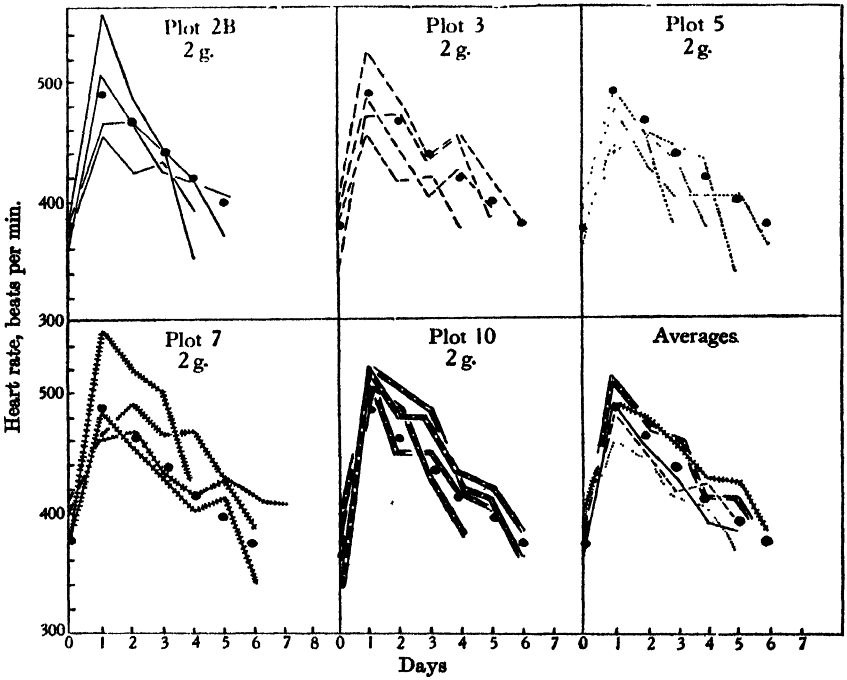

Fig. 2. Comparison of vitamin B_1 activity of wholemeal wheat flours, showing slight inferiority of plot 5 compared with plots 2 B or 3, and slight superiority of plots 7 and 10.

• • • = Comparison curve, mean of all specimens
——— = Plot 2 B
– – – = „ 3
······· = „ 5
+++++++ = „ 7
▬▬▬ = „ 10

accurate comparison. These preliminary results suggest furthermore that the wheat from plot 5 is probably slightly less active than that from plots 2 B or 3, and that from plots 7 and 10 slightly more active. This conclusion was verified in the more precise assay next carried out (Fig. 2). The average duration of cure (taking this as the time following the administration of a dose before the heart rate has again fallen to its initial value) is as follows:

No. of plot	Duration of cure (days)
7, 10	6
2 B, 3	5
5	4

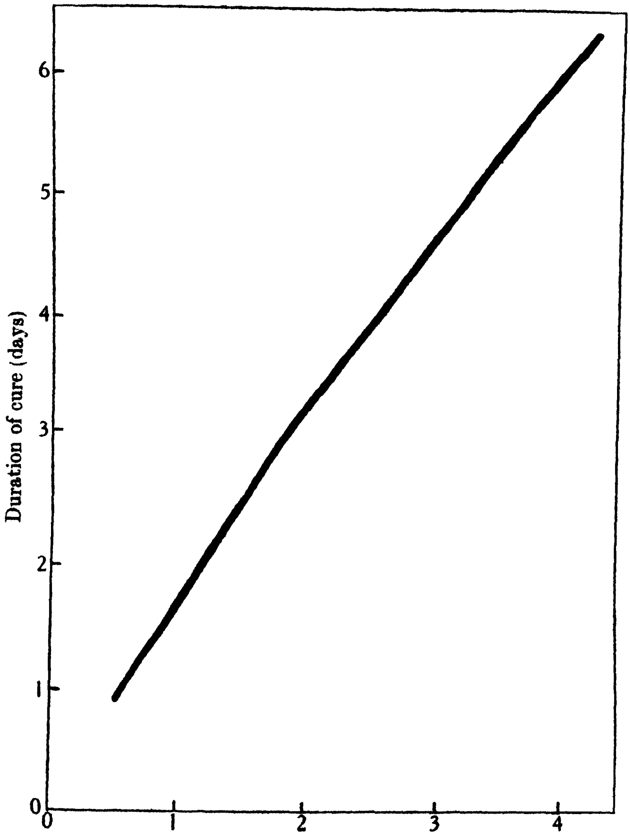

Fig. 3. Dose-effect curve.

For cures of around this magnitude the amount of vitamin fed is known to be approximately proportional to the duration of the cure (Fig. 3; cf. Birch and Harris, 1934). Hence approximate activities may be given as follows, taking the activity of plots 2 B or 3 arbitrarily as 100:

No. of plot	Vitamin B_1 activity
7, 10	120
2 B, 3	100
5	80

The small differences indicated are somewhat greater than the error of the method, and they are evident in each of the various duplicate tests (Fig. 2). They are therefore statistically significant, although of no great magnitude and of little practical importance.

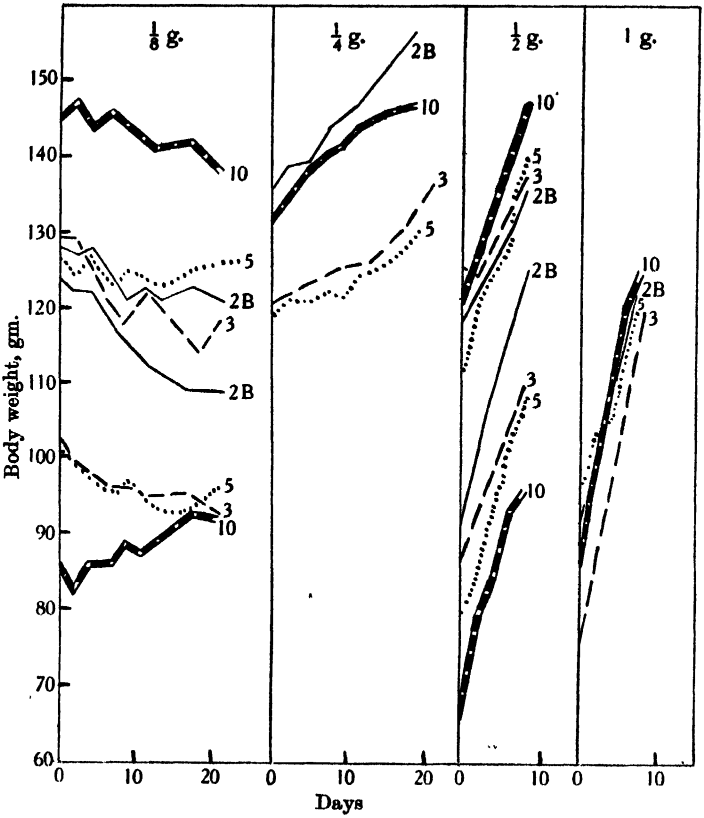

Fig. 4. Vitamin B_1 growth tests on "sharps."

———— = Wheat from plot 2 B
– – – = „ 3
• • • • • • = „ 5
▬ = „ 10

Figures at top allude to *daily dose* allowed to a given group.

RESULTS BY GROWTH TESTS ON "SHARPS."

In conformity with the above conclusions, tests for vitamin B_1 activity by the growth-rate method on specimens of "sharps" prepared from the above four wheats showed that their potencies were of approximately the same order (Fig. 4). All specimens were tested at four levels, viz. $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ and 1 g. per day, and the different response obtained at each level shows that the method was adequately sensitive to detect any notable variation between the specimens, had such existed.

SUMMARY.

Specimens of wholemeal wheat flour from plots given various soil treatment were examined for vitamin B_1 potency by the heart-rate method. The differences detected were not of a striking order, the relative values being as follows: treated with ammonium sulphate = 120; ammonium sulphate plus "complete mineral manure" = 120; dung = 100; no treatment = 100; complete mineral manure = 80. The lack of any striking variation was also confirmed by growth tests on the "sharps" prepared from the several grains.

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STUDIES ON THE MICROBIOLOGY OF GRASSLAND SOIL.

PART I. GENERAL CHEMICAL AND MICROBIOLOGICAL FEATURES[1].

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(With Seven Text-figures.)

INTRODUCTION.

THE chemical and microbiological conditions existing in arable soil have been studied for many years, and much light has been thrown on the mechanism of the principal transformations which occur in soil under arable cultivation. Grassland, however, appears to have attracted singularly little attention in this respect. No doubt this has been due largely to the fact that the inherent hardiness of grassland herbage and its great adaptability to varied conditions of soil and climate have caused it, until recent years, to be regarded differently from arable crops, and the need for a thorough understanding of the factors influencing its growth has hitherto not been acutely felt.

In recent years, however, it has come to be realised that grassland can be made to yield its greatest and best only under conditions of careful cultivation and management. Artificial fertilisers are finding yearly a more extended use on grassland, and it has naturally become increasingly more important to understand the manner in which they affect directly and indirectly its growth and productivity. This knowledge can result only from a careful study not only of the grass itself, its own biochemical processes and the nature of its response to various kinds of treatment, but also from a thorough understanding of the varied and complex relationships which exist between it and the many other forms of animal and vegetable life with which it shares a common growth medium. Apart from work now in progress by Richardson (8) on the behaviour of nitrogenous fertilisers in grassland soils, little attempt appears to have been made to study this problem.

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[1] A preliminary account of this work was given in a paper read before the Biochemical Society in June 1932. See *Chem. and Ind.* (1932), 51, 537.

The object of the present investigation was to obtain information regarding some of the principal chemical reactions and microbiological activities which occur in pasture soil particularly during the growing season; to ascertain the extent to which these may differ in kind or degree from those generally obtaining in arable soil; to trace, if possible, some of the relationships existing between the more important chemical and biological processes occurring in pasture soil, and to observe the manner in which they may be modified by irrigation and by the use of artificial nitrogenous fertilisers to the benefit or otherwise of the grass plant.

EXPERIMENTAL.

The experiment was situated in Whiskers Field at the Agricultural Research Station, Jealott's Hill, Berkshire.

The sward consisted of old pasture, with perennial rye and annual meadow grass dominant, and rough stalked meadow grass and timothy sub-dominant; wild white clover was common, and bent and cocksfoot were also present.

Its manurial and grazing treatment since 1929 had been as follows:

1929 (cut for hay): 1 cwt. nitro-chalk and 7 cwt. potassic basic slag.
1930 (grazed by pigs): 5 cwt. complete fertiliser, 8 cwt. basic slag.
1931 (grazed by pigs): 2½ cwt. sulphate of ammonia, 2 cwt. nitro-chalk.
1932 (experimental year, basal dressing): 6 cwt. superphosphate, 2 cwt. sulphate of potash.

In early March 1932 the experimental area was fenced off, cleared of any residual traces of animal droppings, and rolled to ensure a reasonably flat surface.

The soils forming the subject of this study were those of plots receiving the following treatments:

(1) Control.
(2) Sulphate of ammonia 6 cwt. per acre (2 cwt. each in March, June and July).
(3) Rainfall augmented by weekly overhead irrigation to 0·8 in. per week (*i.e.* a total water supply at the rate of about 40 in. per annum).
(4) Treatments 2 and 3 combined.

There were six replicate plots, each of 9 × 4 ft., for each treatment, these forming part of a larger experiment, laid out in six randomised blocks, and including other treatments not included in the present investigation (4).

Every week during the period March 15th–October 18th with the exception of an interval from mid-July to mid-August the plots under the four treatments were sampled and examined for (1) moisture, (2) ammonia, (3) nitrate, (4) nitrite, (5) *p*H, (6) numbers of bacteria, (7) numbers of actinomyces, (8) numbers of fungi, (9) numbers of actinomyces spores, (10) numbers of fungal spores. For two periods of 8 and 11 days respectively during the spring, determinations were made daily[1].

Sampling and preparation of material.

The cores of soil were taken by means of a 2 in. steel sampling tube to a depth of 4 in., one from each plot, the six replicate cores from any one treatment being bulked in the field.

In order not to interfere with the grass productivity data the soil sampling area was restricted to a strip 1 ft. wide and 4 ft. long, running across the end of each plot. No two cores were taken on any plot from positions less than 2 in. apart, but otherwise they were drawn from random positions. At the end of August, when 20 per cent. of the area had been sampled, a further adjoining 1 ft. strip was brought into use.

The plots were always sampled between 10 and 11 a.m. G.M.T. It was considered necessary always to sample at the same time of the day, since Thornton and Gray (10) have shown that in arable soils bacterial numbers and nitrate nitrogen content vary diurnally, and that maxima occur at approximately 10 a.m. The soils were rubbed through a 3 mm. sieve, all pieces of grass, root and stubble being rejected. The four bulked samples were not dealt with in any particular order: in this, as with the sampling and with subsequent analytical operations, every opportunity of introducing randomness was taken. The samples of sieved soils were always ready for analysis between 3 and 3½ hours after sampling. During this interval, the soils were kept in press-cap jars in the coolest place in the building.

Determination of nitrate and ammoniacal nitrogen.

These constituents were determined in the soil extract obtained by the method described by Olsen (7).

Nitrites were almost always absent, and at no time could more than a slight trace be detected by means of the Griess reagent.

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[1] The original data comprising over 1600 entries are recorded in detail in *Imperial Chemical Industries Agricultural Research Report*, No. A.R.A. 375 dated November 1933.

*Determination of p*H.

The *p*H values were determined by means of the quinhydrone electrode, using a 1–2·5 suspension of the air-dried soil in water.

Microbiological data.

Of the freshly sieved soil 10 gm. were shaken for 4 min. with 250 ml. of sterile saline. Immediately after shaking, 1 ml. of the suspension was transferred by means of a sterile 1 ml. pipette to another flask containing 100 ml. of sterile saline. This gave a dilution of 1 in 2500, which was found to be suitable for the counts of fungi. A further dilution to 1 in 250,000 was used for the counts of bacteria and actinomyces. Plates were poured in quintuplicate. The medium used for bacteria and actinomyces was that described by Thornton (11), and the period of incubation was 10 days. The fungi were poured with Waksman's peptone glucose agar (12) and incubated for 3 days. A fungus spore count was obtained by the method described by McLennan (6), which method was also used to obtain an estimate of the proportion of actinomyces colonies arising from spores, in so far as this method may be applicable to these organisms.

For comparative purposes an actinomyces count was obtained, using the medium suggested by Rao and Subrahmanyan (9).

All count data are referred to 1 gm. of oven-dry soil.

Rainfall.

For purposes of reference in studying the data presented below, the weekly figures for rainfall and average soil temperature at 4 in. depth during the period covered by this work are shown in the following table.

Table I.

Date 1932	Soil temperature ° F. at 4 in.	Rainfall during previous week in.	Date 1932	Soil temperature ° F. at 4 in.	Rainfall during previous week in.
Mar. 15th	35·8	0·16	July 5th	65·0	0·49
22nd	43·0	0·02	12th	68·0	0·41
29th	43·1	0·71	Aug. 16th	64·1	0·25
April 5th	44·0	0·81	23rd	64·0	1·37
12th	40·1	0·62	30th	66·0	0·03
19th	42·1	0·45	Sept. 6th	61·3	0·57
26th	46·0	0·55	13th	58·1	0·53
May 3rd	51·0	0·96	20th	56·0	0·27
10th	46·0	0·90	27th	52·1	0·38
18th	56·0	0·28	Oct. 4th	47·6	0·62
24th	55·4	1·90	11th	50·3	0·45
31st	55·8	1·03	18th	51·1	0·63
June 7th	57·2	0·27	Nov. 1st	40·5	2·76
14th	61·2	0·26	15th	42·0	0·61
21st	61·1	0·00			
28th	66·0	0·11			

Herbage yield data.

The plots were cut at regular intervals during the grazing season, when the herbage was at the grazing stage. The yields obtained from all the treatments, including those not studied in the present investigation, will be discussed in detail, and in relation to the data from other experiments, in another paper (4). However, in order to enable the soil data presented below to be considered in relation to the productivity of the herbage, a summary of the yields obtained from the four treatments here under consideration is given below.

Total yields of dry matter obtained during the season.

	cwt. per acre
Control	65·3
Sulphate of ammonia, 6 cwt. per acre	85·0
Irrigation to level of 0·8 in. per week total water supply	88·8
Sulphate of ammonia and irrigation	105·4

The variations in yield during the season were generally similar for all four treatments, with the usual peak for the spring flush (May) and the smaller secondary peak for the early autumn flush (September).

I. CHANGES IN THE LEVELS OF AMMONIA- AND NITRATE-NITROGEN IN THE TOP 4 in. OF GRASSLAND SOIL DURING THE GROWING SEASON.

The data have been plotted in Figs. 1–4.

During the early part of the season (mid-March–end May) the *amount of nitrate-nitrogen* decreased from 8–10 p.p.m. to 2–3 p.p.m. (on oven-dry soil). This low level was maintained, with only a slight tendency to rise, until mid-October, the spring level of 8 p.p.m. being again reached, on the irrigated soil, during November. The *amount of ammonia-nitrogen* rose with fluctuations from an initial spring value of 4–5 p.p.m. until, after an interval from mid-July to mid-August when no samples were taken, it showed a maximum value of about 18 p.p.m. in August, subsequently declining to 13 p.p.m. in November. Thus throughout the growing season the concentration of ammonia-nitrogen was high and that of nitrate-nitrogen low (cf. Richardson (8)), a state of affairs which is no doubt attributable to the poorer conditions for nitrate accumulation normally existing in grassland soil. The inverse relationship which appears to exist between the ammonia and nitrate-nitrogen is shown particularly well from daily samplings (Fig. 1 inset).

(*a*) *Effect of irrigation.*

Reference to Fig. 1 shows that in the spring, when the soil moisture content was in the neighbourhood of 20–25 per cent., the extra water supplied by the irrigation on the whole depressed the amounts of ammonia and nitrate-nitrogen. During the drier weather in June, however, the levels of both ammonia and nitrate-nitrogen rose on the irrigated plots and remained, with few exceptions, 2–3 p.p.m. higher right through to November.

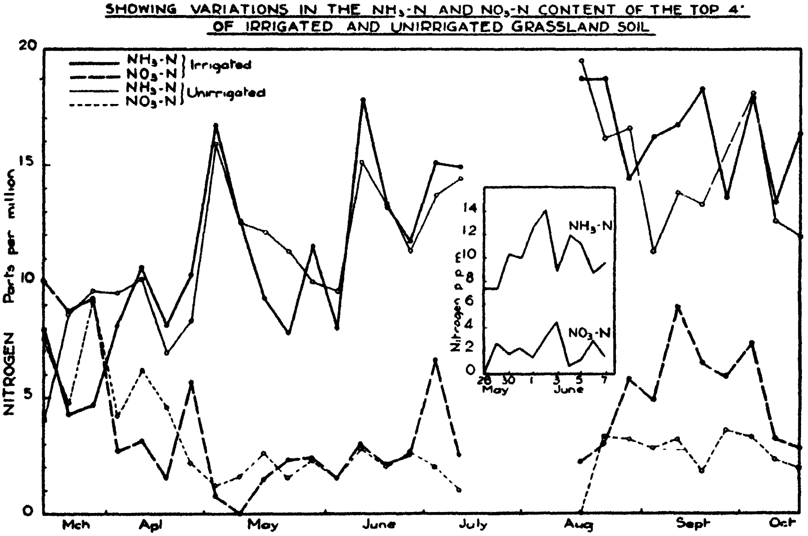
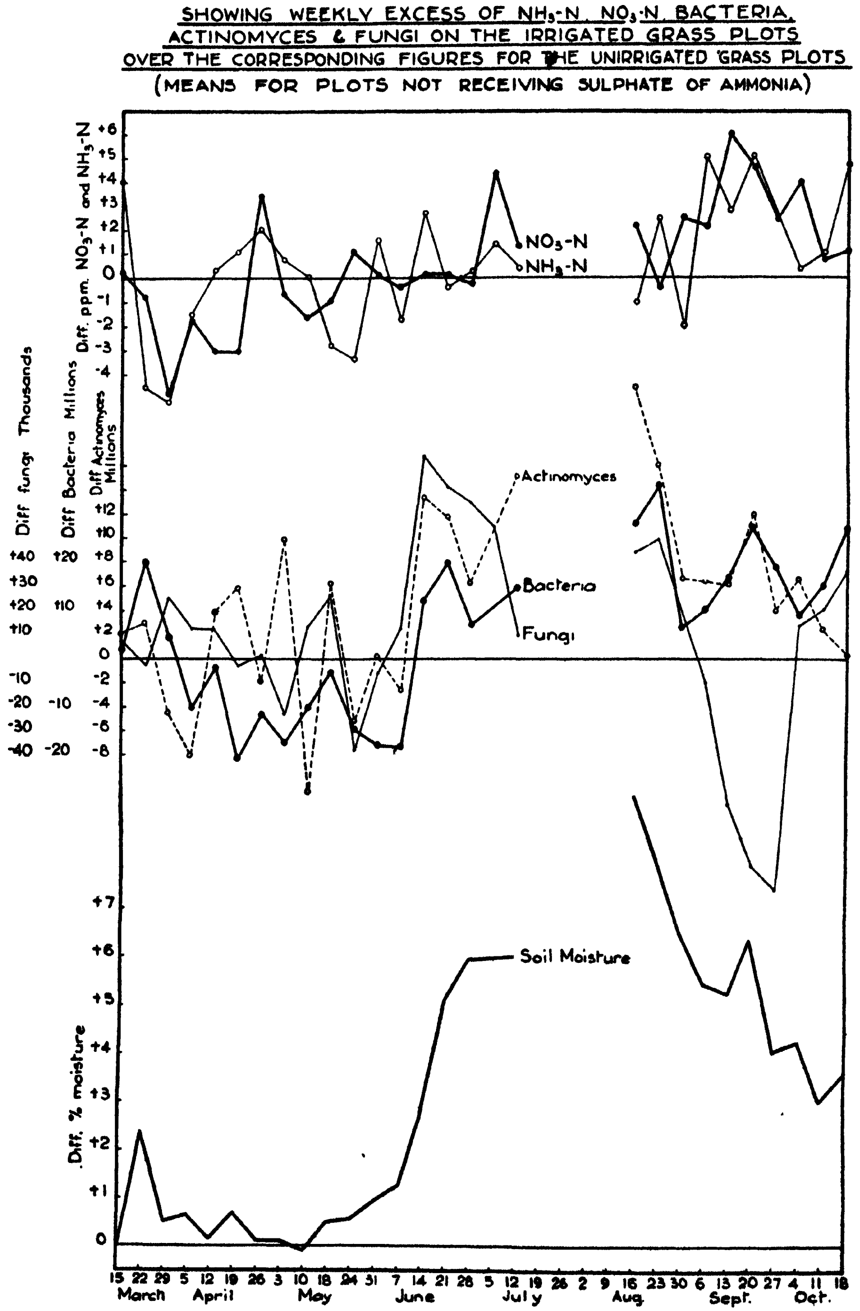


Fig. 1.

These changes in levels of ammonia and nitrate-nitrogen in the plots receiving no nitrogen are shown at the top of Fig. 2 as regressions with time of the *differences* between the values on the irrigated and unirrigated plots. The straight line regressions of both these graphs are statistically significant (ammonia-nitrogen, odds = 40 : 1; nitrate-nitrogen, odds = 18 : 1). Since the total amount of nitrogen added in the irrigation water during the season was not more than 4 lb./acre, it would appear that the irrigation aided the breakdown of the organic reserves of the soil, with the consequent production of additional ammonia and nitrate. These increases in the amounts of ammonia and nitrate-nitrogen are closely associated with increased numbers of bacteria, actinomyces and fungi (see Fig. 2), and were accompanied by increased yields of herbage.



SHOWING WEEKLY EXCESS OF NH_3-N, NO_3-N, BACTERIA, ACTINOMYCES & FUNGI ON THE IRRIGATED GRASS PLOTS OVER THE CORRESPONDING FIGURES FOR THE UNIRRIGATED GRASS PLOTS

(MEANS FOR PLOTS NOT RECEIVING SULPHATE OF AMMONIA)

Fig. 2.

On the plots receiving nitrogen the corresponding regressions cannot be considered significant (ammonia-nitrogen, odds 5 : 1; nitrate-nitrogen, odds 4 : 1).

(*b*) *The effect of added nitrogen.*

Nitrogen in the form of sulphate of ammonia was applied to the requisite plots at the rate of 2 cwt. per acre on March 15th, June 2nd and July 28th. The analytical figures show that both in March and July an excess of ammonia was still present 4–5 weeks after the sulphate of ammonia had been applied to the soil (Figs. 3, 4). The rate of transformation or uptake of the added ammonia was undoubtedly controlled in the early spring by the low soil temperature, while in July moisture was obviously the limiting factor. In early June, when moisture and temperature conditions were both favourable, the excess of added ammonia had

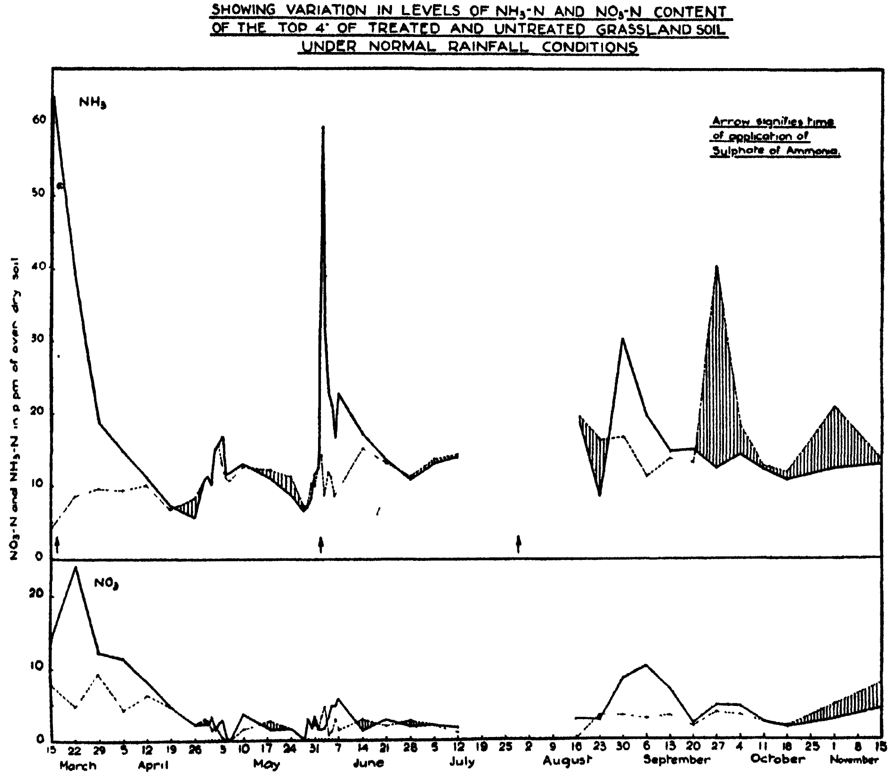


Fig. 3.

almost completely disappeared in three or four days (cf. Richardson (8)). On each occasion the disappearance of the ammonia-nitrogen was accompanied by a definite, though smaller, increase in the nitrate nitrogen, the excess being greater in March than in June, when it was presumably more rapidly utilised by the herbage.

SHOWING VARIATION IN LEVELS OF NH_3-N AND NO_3-N CONTENT OF THE TOP 4 OF TREATED AND UNTREATED GRASSLAND SOIL UNDER IRRIGATED CONDITIONS

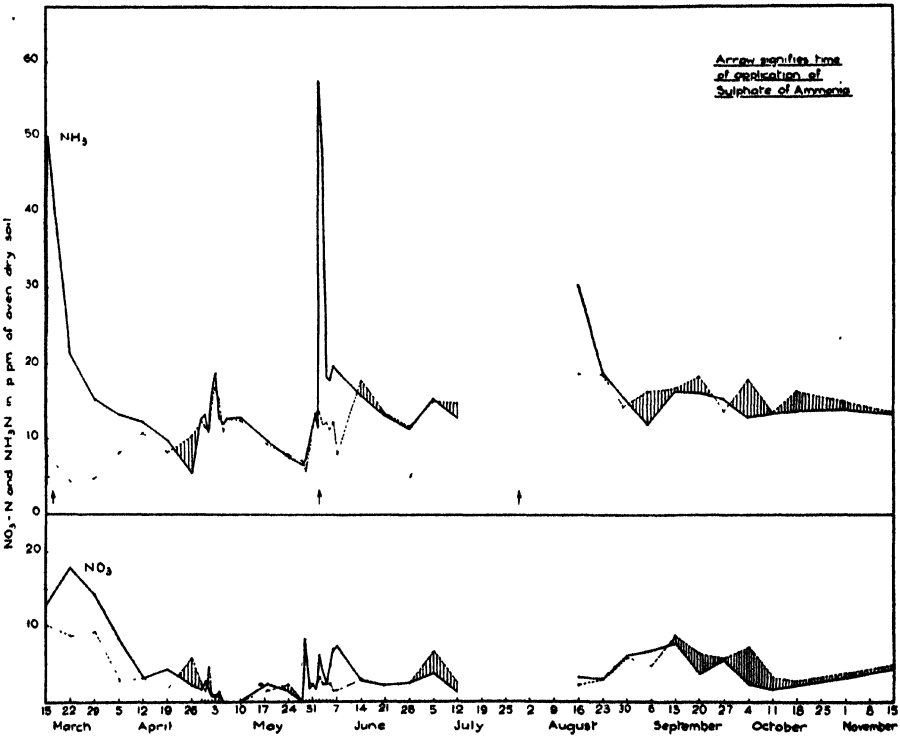


Fig. 4.

Reference to Figs. 3 and 4 also shows that whereas in March the curve for the ammonia transformation is comparatively smooth, the curves for the June and apparently also for the July applications show distinct secondary peaks. Both curves also show that in the treated soil the ammonia and, at least on the irrigated soil, the nitrate subsequently tend to run at a lower level than on the untreated soil (shaded area). This is chiefly evident in the curve following the July application, and is possibly an indication that the added sulphate of ammonia has lowered the rate of ammonification from organic matter, a conclusion which is supported by the fact that the numbers of bacteria were significantly depressed at this time on the nitrogen-treated plots (Fig. 7).

II. CHANGES IN THE *p*H OF THE SOIL DURING THE SEASON.

In common with all the other soil factors recorded in this experiment, the *p*H fluctuated markedly from week to week, but certain trends were apparent. The soil on the control plots became progressively more acid as the season advanced, reaching a point of maximum acidity in September. Thereafter the reaction tended to become less acid, until at the end of the season it approximated to its spring value. This development of acidity is doubtless connected with the accumulation of solutes in the top layers of the soil under the influence of transpiration and evaporation.

(*a*) *Effect of irrigation.*

On the irrigated plots the *p*H remained almost constant throughout the season, there being a tendency even to rise. This can be attributed definitely to the fact that the local water-supply was used for the irrigation, an adequate quantity of soft water not being available during this season. Analysis of the water showed that 17 cwt. of total solids were added per acre, of which the chloride and bicarbonate content were without doubt sufficient to affect the soil reaction.

(*b*) *Effect of added nitrogen.*

On the nitrogen-treated plots the change in *p*H was similar to that which occurred on the plots receiving no nitrogen but, in keeping with the acidifying nature of the fertiliser, the increase in acidity was slightly greater and an autumn recovery to the spring value was not quite attained.

III. VARIATIONS IN THE RELATIVE ABUNDANCE OF BACTERIA, ACTINOMYCES AND FUNGI DURING THE SEASON.

Reference to Fig. 5 shows that the soil micro-organisms are subject to very wide and rapid fluctuations in numbers. Indeed, during one of the periods when daily counts were made, in the interval April 29th–30th, the numbers of bacteria and actinomyces colonies developing on the count plates declined from 125 millions/gm. dry soil to approximately 50 millions. This sharp drop was followed by a steady rise, the numbers reaching 150 millions after 6 days. Similar changes were observed under all four treatments, so that there is no cause to doubt the reality of the fluctuation; in fact, throughout the whole of the season the changes in bacterial numbers were markedly parallel for the four soil treatments, and differed from one another only in respect of the gradual changes of level caused either by the manuring or by the irrigation.

The data plotted in Fig. 5 show that *actinomyces and bacteria* were present in much greater numbers, 50–80 millions per gm. dry soil, during the period April–May, and that during the hot, relatively rainless weather in June, July and August their numbers fell to 10–20 millions. During September and October the numbers rose again almost to the spring level, but declined again in November to 20–30 millions. Conn (1), and Cutler, Crump and Sandon (2), have already shown that high numbers occur at such times in arable soils, but numbers in grassland, as would be expected from the larger organic matter content, are considerably higher than in arable, and the fluctuations also are much greater.

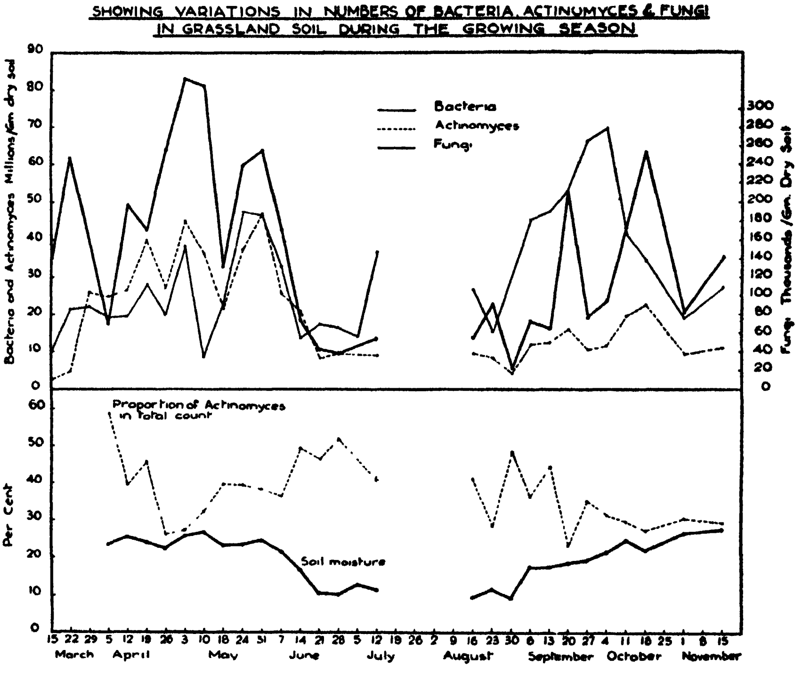


Fig. 5.

The *relative proportion of actinomyces and bacteria*, as indicated by the colonies developing on asparagin-mannitol agar, remained fairly steady throughout the season, lying between the limits 25–50 per cent. actinomyces. The curve shown in the lower half of Fig. 5 indicates that the proportion of actinomyces is low during wet weather and high during dry weather. Actinomyces therefore seem better able to withstand dry soil conditions than bacteria, which in their turn tend to flourish relatively more during the wetter periods of spring and autumn.

The *counts of fungi* averaged 90,000 per gm. dry soil during the spring months, rarely rising above 140,000 or falling below 40,000. During September and October, however, counts were invariably above 140,000. The highest counts, 260,000 and 280,000, were obtained during late September. The warm dry conditions of June and July caused a marked decline in numbers. The differences in the respective levels in spring and autumn may be related to changes in the reaction of the soil: *p*H values on the normal pasture averaged 6·5–6·6 in April, and fell to 6·2–6·3 during August and September. This in itself would tend to suppress bacteria and actinomyces; the fungi, being more acid tolerant, would be favoured by reason of the reduced competition. It is noticeable that the reverse holds during October, when the *p*H values indicate a change in the direction of neutrality.

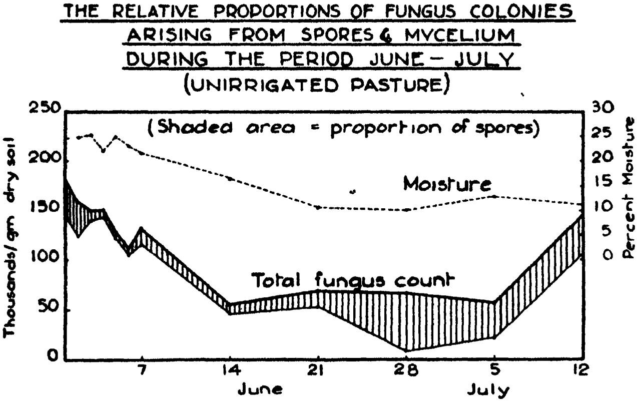


Fig. 6.

This *relation between the change of p*H *and the relative proportions of bacteria plus actinomyces* (B + A) *and fungi* (F) is quite pronounced and is in agreement with the findings of Jensen (5) that an increase in acidity is accompanied by an increase in the ratio $F : B + A$. From the nature of his material Jensen was unable to find evidence of this relationship at *p*H values numerically greater than 6·0. The values obtained in this experiment show that the ratios varied as follows between *p*H 5·8 and 6·8.

Table II.

*p*H interval	No. of observations	Mean ratio $\frac{F}{B+A}$
5·8–6·1	7	0·0061
6·1–6·2	8	0·0034
6·2–6·3	11	0·0032
6·3–6·4	16	0·0031
6·4–6·5	15	0·0021
6·5–6·6	19	0·0024
6·6–6·8	26	0·0025

Thus the relationship to which Jensen drew attention certainly still exists above *p*H 6·0. With twenty-one Danish soils of widely different character Jensen obtained a mean ratio of 0·0077 for the *p*H range 6·0–7·0.

Table III. *Showing effect of soil moisture on the relative amounts of actinomyces and fungus mycelium and on the relative abundance of spores.*

No. of observations	Mean 4 in. soil temp. °F.	Soil moisture Mean %	Soil moisture Range %	Actinomyces Mycelium 10⁶/gm.	Actinomyces Spores 10⁶/gm.
4	65	8·9	6–10	5·5	1·6
8	65	11·2	10–14	8·7	2·2
7	62	17·3	14–18	14	1·9
12	62	19·6	18–22	20	2·9
22	58	24·2	22–26	24	2·9
12	57	27·1	26–30	31	2·9

No. of observations	Mean 4 in. soil temp. °F.	Fungi Mycelium 10³/gm.	Fungi Spores 10³/gm.	Proportion actinomyces spores in total actinomyces count (%)	Proportion fungi spores in total fungi count %
4	65	60	39	22	39
8	65	57	32	20	36
7	62	134	18	12	12
12	62	92	39	13	30
22	58	133	16	11	10
12	57	153	20	8·5	12

With regard to the *influence of moisture on the abundance of micro-organisms*, particularly actinomyces and fungi, a discrimination must obviously be made between vegetative mycelium and inactive spores, since, if the number of spores increases with decreasing moisture, the effect of moisture will be masked to a large extent in so far as numbers may be determined by the ordinary dilution method, which does not discriminate between spores and mycelium. By means of the counts of actinomyces spores and fungal spores which were made during June–

September by platings of samples desiccated according to the method proposed by McLennan (6), it was possible to differentiate between the effect of moisture on the amount of mycelium and on the number of spores. During the dry conditions of June and July there was relatively little live fungus mycelium present in the soil, whereas during the same period the actinomyces were present mainly in the active mycelial condition, the colonies arising from spores at no time amounting to more than 22 per cent. of the total. Fig. 6 shows graphically the proportions of fungal spores to active mycelium during this period.

Table III summarises the data obtained when the counts are classified according to the moisture content of the soil. It will be seen that decreasing moisture causes a decrease in the numbers of active actinomyces and fungi, the decrease being much more pronounced with the first mentioned. With regard to the spores, whereas the number of fungal spores increases with decrease in moisture, the number of actinomyces spores is reduced along with that of active actinomyces. These two facts suggest very strongly that actinomyces are more sensitive to changes in moisture content of the soil than are fungi. The soil temperature changed very little during June–September, so that the changes in numbers observed are relatively free from what might otherwise be a complication.

(a) *The effect of irrigation on the soil microflora.*

During the months of April and May bacterial numbers were on the whole higher than at any other time during the growing season. Irrigation tended to depress bacterial numbers during this time, and it was not until early June, when the 9 a.m. soil temperature at 4 in. rose to above 55° F. and the soil moisture content fell below 20 per cent., that the case was reversed.

From June to the end of the growing season (mid-October) bacterial numbers were consistently higher on the irrigated plots, the percentage excess being very closely related to the excess percentage of moisture (Fig. 2). Since the weekly estimations of bacterial numbers were made on the sixth day after irrigation, the effect of the water, particularly during the warm midsummer period, was probably greater than is revealed by the data.

Actinomyces were affected in a similar way to the bacteria.

During the hot, dry midsummer period, fungal numbers were also definitely higher under irrigated conditions, but during September and October, when the mean moisture content of the irrigated plots was higher than in the spring, the numbers were lower than on the unirrigated plots.

EXCESS NUMBERS OF BACTERIA, ACTINOMYCES & FUNGI ON NITROGEN TREATED PLOTS OVER THE CORRESPONDING NUMBERS ON THE PLOTS RECEIVING NO NITROGEN.

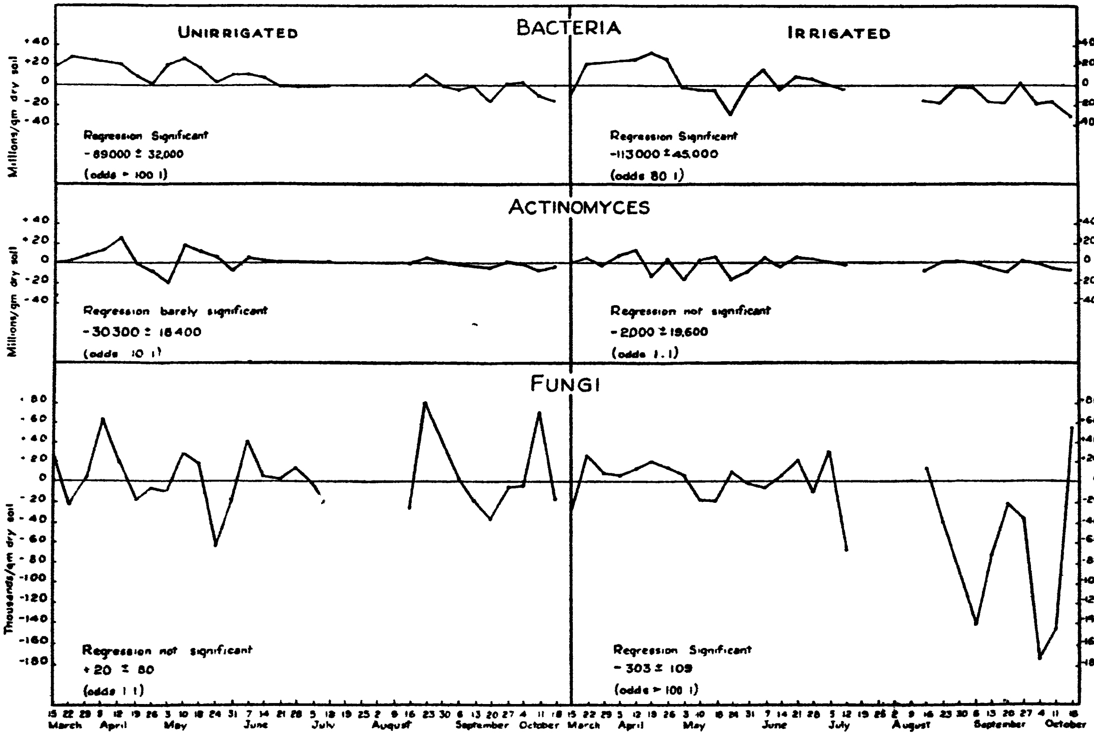


Fig. 7.

(*b*) *The effect of the addition of sulphate of ammonia on the soil microflora.*

Owing to the comparatively large fluctuations in the weekly data obtained for bacteria, actinomyces and fungi, a direct comparison with a view to determining the effect of the added nitrogen is obscured. This disturbing effect is to a large extent eliminated, however, by considering the weekly variations of the *differences* between the values for the nitrogen-treated plots and the corresponding values for the plots receiving no nitrogen. The trends of these differences both for the irrigated and unirrigated plots are shown graphically in Fig. 7.

It will be observed that the numbers of bacteria were slightly increased by the addition of the first dressing of nitrogen, but that the subsequent dressing had little or no effect; in fact, towards the end of the season numbers were definitely lower on the plots that had been treated. Actinomyces appeared to be similarly affected, though to a smaller and non-significant extent; fungi appeared to be unaffected except under irrigated conditions. This progressive lowering of the numbers of bacteria, and perhaps of actinomyces, during the season is consistent with the smaller amounts of ammonia and consequently nitrate found on the nitrogen-treated plots during the second half of the season, and is probably due partly to the more acid reaction of the treated soil resulting from the sulphate of ammonia and partly to the somewhat lower moisture content due to the greater amount of water transpired from the larger amount of grass.

DISCUSSION.

The data here presented show that the activity of the soil micro-organisms in grassland is controlled primarily by the temperature and the moisture content of the soil. Numbers were low during the winter by reason of the low temperature in spite of the high moisture content. In summer numbers were again low, this time owing to lack of moisture. It is usually only during spring and autumn that both these factors are simultaneously favourable, and these two periods are, as would be expected, characterised by increased microbiological activity. Furthermore, since the soil usually contains for a given soil temperature range a greater amount of moisture in spring than in autumn, numbers are usually greater in spring than in autumn; a difference which is probably accentuated by the less favourable soil reaction in autumn. These periods of microbiological activity are also the periods which are characterised by strong and rapid growth of the herbage. It is interesting to note (3) that the numbers of worms in grassland soil vary in an exactly similar way, there being maxima in spring and autumn. The relation, then, between the grass and the soil micro-organisms is a very close one; both rely to a very large extent on an adequate moisture supply and sufficient warmth. Providing these are favourable, there is nothing to prevent the whole of the soil flora and fauna being active, all taking their respective parts in the processes of decomposition and assimilation. It is not, however, likely that the same conditions of temperature and moisture would suit equally well all the forms of life existing in the soil, and there must presumably be a time in the early spring when the temperature is sufficiently high for some forms to become active, but is still too low for others. It is probably just such conditions as these that limit the growth of grass in the early spring, in the sense, that although the temperature and moisture conditions are favourable for the growth of the grass, it is unable to respond owing to the temperature being still too low for the micro-organisms concerned in liberating the requisite available nitrogen.

With regard to most of the other effects observed, it is necessary to emphasise that the grass was cut by hand at various intervals throughout the season, and that none of the material so removed was ever returned to the plots. Under grazing conditions probably about 90 per cent. of the nitrogen would have been returned, and much of this would have entered again into the cycle of transformations. While this method of defoliation may be criticised adversely as being a departure from natural grazing conditions, it nevertheless has the great advantage that it may exaggerate some of the changes which go on in the soil, and so make them easier to discover.

SUMMARY.

1. Pasture soil was found to be characterised by relatively high ammonia and low nitrate-nitrogen content during the main growing period (May–September). Applications of sulphate of ammonia while initially raising the ammonia and nitrate-nitrogen levels, ultimately led to a lowering. The effect of irrigation during the spring, when the soil moisture content was high, was to depress the ammonia and nitrate-nitrogen levels, but during the dry summer months and subsequently the levels were appreciably raised.

2. A small though definite periodic change in the reaction of normal grassland soil took place during the season, the soil being most acid during the summer. Added sulphate of ammonia slightly accentuated the change, and the return to normal in the autumn was not quite attained.

3. Bacteria and actinomyces were present in much greater numbers (50–60 millions/gm. dry soil) during the period April/May than at any other time of the year. The numbers were depressed (10–20 millions) during the hot summer months, owing to the lack of moisture, but increased again (30–40 millions) with the moisture soil conditions in September. During the winter the numbers fell to approximately the summer levels. The fungal counts, on the other hand, were much higher in the autumn than in the spring.

There were thus two well-defined periods of microbiological activity: April–May and September–October, corresponding to the two flushes of growth on grassland.

Although numbers of bacteria and actinomyces were depressed during summer, the latter appeared to be relatively more tolerant of dry conditions, in that their proportion increased at this time.

Lack of moisture in the summer was accompanied by an increase in the number of fungal spores, but a decrease in the number of actinomyces spores.

The effect of nitrogen added in the form of sulphate of ammonia, on numbers of bacteria and actinomyces, is small in comparison with the marked influence of moisture and temperature. During the relatively dry summer months, irrigation maintained numbers of bacteria, actinomyces and fungi at a definitely higher level.

4. The evidence so far available indicates that in grassland soils the up-grade and down-grade processes of the nitrogen cycle are no different in nature from those in arable soils, but the level of intensity of these processes is higher. Owing to the different conditions in grassland soils—especially the plentiful supply of organic matter derived from the dense mass of roots and herbage debris—the population of micro-organisms is greater and the fluctuations in their numbers are more rapid and intense.

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The author desires to record his gratitude to Mr H. J. Page, who has given much helpful advice and criticism during the conduct of this work. Special thanks are due to Mr W. J. Shaw Hodges, who rendered valuable assistance, and who was responsible for the determinations of nitrate and ammonia. To Miss S. Colsell also, considerable credit and thanks are due for the careful and painstaking way in which she carried out the many statistical computations. Thanks are also due to Messrs Imperial Chemical Industries, Limited, for permission to publish this paper.

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PARALYSIS AND AVITAMINOSIS A IN SWINE.

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(With Two Text-figures.)

INTRODUCTION.

THIS communication deals with an abnormal condition, diagnosed later as swine paralysis, which developed unexpectedly in certain experimental animals being fed rations recommended for general use in this country; it describes the successful treatment of the condition by the addition of vitamin A supplements to the diet; and it presents determinations of the vitamin A and carotene content of the foodstuffs and of the reserves of the animals leading to an approximate estimate of the requirement of growing swine for vitamin A.

As far as is known the present instance is the first in which this condition in swine has been recognised as being due to vitamin A deficiency in this country, although it occurs under the adoption of practical methods of husbandry. It has also occurred, as will be shown later, at other research institutes in Great Britain and on the continent without a suitable explanation being put forward for its presence.

Piglings had been selected from four litters and placed on experiment when 12 weeks of age. The object of the experiment was to determine the effect of the mineral and vitamin D content of the diet on the utilisation of the food consumed. The animals had been randomised over five treatments consisting of different amounts of mineral and vitamin D supplements added to an otherwise supposedly adequate basal diet, while a fish-meal control group was also included. About 8 weeks after this experiment commenced, symptoms of what appeared at first to be rickets developed in the animals. No relationship was found to exist between the incidence of the disease and the particular treatment being imposed at the time, since animals under all conditions of treatment were affected. It was noticed, however, that animals with the disease had been selected from two litters and that the treatment of these, previous to being placed on the experiment, was different from that of the animals which remained normal.

EXPERIMENTAL.

The animals selected for our study had been used in an earlier experiment in which certain rations were being tested to determine if they contained adequate amounts of particular growth factors shown to be necessary for rats. Of the four litters, two had been fed small doses of liver daily (4 oz. per head) for 4 weeks previous to weaning. The piglings were weaned at 8 weeks of age. For 4 weeks afterwards certain animals in these two litters continued to receive the liver supplement, while the others were allowed an equi-caloric supplement of fish meal. The remaining two litters were fed the fish-meal supplement in addition to their meal ration while being suckled by the sows, and certain animals selected at random from each litter continued on this supplement after weaning. In the treatment of the remaining animals in these two litters the fish meal was replaced by the liver supplement after weaning.

At the end of this experiment when the animals were 40–50 lb. live weight at 12 weeks of age, the second experiment, in which diets of different mineral content were being compared, was commenced. The groups in the previous experiment were randomised over the new treatments giving the following arrangement:

	Group			
Treatment	1	2	3	4
4–8 weeks of age	Liver	Liver	Fish meal	Fish meal
8–12 „ „	Liver	Fish meal	Liver	Fish meal
Total number of animals	6	6	9	9
Of these—No. of animals which received (from 12 weeks onward):				
(1) High mineral diet	2	2	3	3
(2) Low mineral diet	3	3	4	5
(3) Fish-meal diet	1	1	2	1

This grouping of the animals offered a possible explanation of the abnormal condition, since it was only animals in group 4 which showed signs of malnutrition and the symptoms developed irrespectively of the ration being fed at the time of their appearance.

Since the disease appears to be dependent on the early nutrition of the animals some further relevant particulars are given.

The dams of the animals selected for experiment were at pasture up to 1 week before farrowing, when they were confined to comfortable quarters with access to sunlight till their offspring were weaned. The sows were fed during this period a mixed ration consisting of: 30 parts wheat middlings, 30 parts barley meal, 10 parts bean meal, 10 parts wheat meal, 10 parts bran, and 10 parts fish meal.

While being suckled, the young animals had access to a ration of 2 parts flaked maize and 1 part crushed beans, which they gradually commenced to eat when about 4 weeks old.

After weaning the diets used were

A		B	
65 parts	barley meal	30 parts	barley meal
25 ,,	wheat middlings	25 ,,	oats
10 ,,	fish meal	30 ,,	white sharps
		15 ,,	soya-bean meal.

Two mineral mixtures were fed in conjunction with ration B after the animals were 12 weeks of age:

(1)	(2)
4 lb. $CaCO_3$	2 lb. $CaCO_3$
½ lb. NaCl	½ lb. NaCl
1 oz. Fe_2O_3	1 oz. Fe_2O_3.

The above amounts were added to every 100 lb. of the ration. Drinking water was allowed *ad lib.* and also mixed with the food.

Fish meal, after having been reduced to 5 per cent. of the ration when the animals reached 70 lb. live weight, was completely withdrawn from ration A when the animals reached 150 lb. The soya-bean meal was gradually reduced during the experiment till only 5 per cent. was included in ration B when the animals reached 200 lb. live weight.

It is worthy of note that the young animals received no green food nor were they allowed out to pasture. It is fairly certain, however, that the raw liver fed as supplement to the diet supplied most of the dietary constituents which the young animals would obtain if green food had formed part of the dietary. Bearing this in mind it may be claimed that the groups rearranged as above represent four distinct methods of rearing piglings under practical conditions of swine husbandry. In practice group 1 represents those animals which receive abundant green food during the suckling period and are at pasture for some time after weaning. Those animals which, after weaning, are fattened off straightaway indoors correspond to group 2. The treatment of the third group is characteristic of the practice of rearing indoors followed by a store period at pasture, while group 4 represents strict confinement under winter conditions of management when green food is unobtainable. Otherwise, the conditions of management can only be described as those of good farm practice, since up till weaning the animals were the property of the Cambridge University Farm.

The technique adopted in feeding the animals after they reached about 40 lb. live weight has been reported in a previous communication in which the plane of nutrition and the method adopted in calculating the results for growth rate are also given (1).

RESULTS.

Growth.

All animals in groups 1, 2 and 3 (twenty-one in all) reached 200 lb., at which weight they were slaughtered for the analysis of various body organs. Each animal consumed the whole amount of its daily ration, leaving no residue. Live-weight increase was uniform throughout, little variation occurring either between the individuals or the groups. The growth of these animals must be described as normal (Table I).

The reaction of the animals in group 4 was totally different (Table II). No animal reached 200 lb. live weight on the treatment imposed. All refused to consume a part of their daily ration, usually 8–10 weeks after weaning. Decreasing planes of nutrition were assumed till growth ceased and the live weights of the animals began to decline. This effect was obtained irrespectively of the mineral content of the ration. It was noticed, however, that while the animals consumed their total daily food allowance their growth rate was similar to that obtained in the other groups.

Table I. *Growth-rate records of animals.*

Figures: Actual live weights of animals 15 weeks after reaching 50 lb.

	Group			
Ration	1 L.L.	2 L.O.	3 O.L.	4 O.O.
B, 4 % $CaCO_3$	166	162	169	Killed
	174	174	177	145
	—	—	170	140
B, 2 % $CaCO_3$ and A	183	185	180	124
	186	187	181	117
	189	177	182	143
	181	189	189	148
	—	—	179	179
	—	—	189	177
Average:				
B, 4 % $CaCO_3$	170	168	172	142·5
B, 2 % $CaCO_3$ and A	184·8	184·5	183·3	148·0

L.L. = liver fed for 4 weeks during suckling and 4 weeks after.
L.O. = liver fed for 4 weeks during suckling and fish meal for 4 weeks after.
O.L. = fish meal for 4 weeks during suckling and liver for 4 weeks after.
O.O. = fish meal for 4 weeks during suckling and 4 weeks after.

All the animals in this group, one after another, developed the same distinct symptoms of a disease which was new to the author's experience of swine husbandry. Marked symptoms of any abnormality were only apparent some time after the animals had ceased to consume their daily allowance of food and had begun to assume decreasingly lower planes of nutrition. Lack of co-ordination of movement leading to a swaying gait and later to a complete loss of control of the hindquarters soon followed. Forward movement was only possible by using the forelimbs and drawing the hindquarters along the ground. When control of the forelimbs was lost the animals remained lying on their flanks and any attempt to move or even the presence of an attendant caused spasms which shook the whole body. When fed, the head required to be raised forcibly and the body propped up to allow proper consumption of the food. When it was apparent that death must follow sooner or later, if the ration continued to be fed alone, recovery treatment using various vitamin concentrates was commenced. Two animals were killed off as controls at this stage and an examination made of various body organs.

Curative treatment.

The disease did not appear to be the result of faulty mineral metabolism as it occurred in animals on high calcium, medium calcium and fish-meal diets which were sufficiently varied in mineral content to rule out this possibility. It was decided therefore to commence vitamin therapy and determine if any specific vitamin exercised a curative effect. Since the rations were composed largely of whole cereal grains it was unlikely that additional doses of vitamin B to the ration would exercise a beneficial effect. Vitamin B therapy therefore was not attempted. As a vitamin C concentrate orange juice was chosen, vitamin A was supplied as crystalline carotene and cod-liver oil was used as a vitamin A and D supplement. Each of these substances was fed to two animals when growth had ceased. The response to the different treatments was remarkable (Fig. 1) in so far as each concentrate exerted a marked effect on the animals. Daily doses of 5 ml. of cod-liver oil, 10 mg. of crystalline carotene in coconut oil or 40 ml. of orange juice per 100 lb. live weight proved sufficient to restore the appetites of the affected animals and normal growth resulted usually within 21 days. The sole exception proved to be one of the animals (No. 284) receiving orange juice which only showed partial recovery of growth compared with the others. Correlated with the resumption of normal growth was the marked change in the clinical condition. Spasticity and incoordination diminished and the animals

Table II. *Weekly live-weight records of group 4 animals (in lb.). Records of fastest growing animal (No. 300) and slowest growing animal (No. 279) in groups 1, 2 and 3 (on B, 2 per cent.* $CaCO_3$*) included for comparison.*

No. and sex																								
Ration B, 2 % $CaCO_3$.																								
300 G	43	48½	53	60	68	76½	84	93½	100	109½	118	129	138½	150½	162	170½	186	199						
279 H	42½	47	53	61	67½	74½	80	89½	98	107	115½	125½	136	144½	156	164½	174	185						
293 H	**45**	**47½**	**54**	**60½**	**69**	75	82	**83½**	**90**	99	[105½]	**109½**	**117**	**122**	**126**	**131**	**140**	**150½**	N.W.	N.W.	N.W.	N.W.	N.W.	**142**
288 G	51	**54½**	**59**	66	**73**	**74½**	**81**	**86**	[87]	**93½**	**99½**	**93**	100	102½	{**107½**	**115**	124½	135	142½	150½	160½	171	179}	
																		Cod-liver oil therapy						
285 H	**44**	50	**55½**	**61½**	69	**73**	**74½**	**80**	**79**	**85**	**89**	**[96]**	**98½**	**103½**	**106**	{**115½**	124	134½	143½	154	160½	165	175}	
																		Orange-juice therapy						
284 H	40	**46**	**50½**	58	65	70	78	**84**	**85½**	**90**	**99½**	108	**115**	**119½**	**124**	**132**	[141]	**147**	**151**	{N.W.	**155**	**159½**	**168**	**171**}
																					Orange-juice therapy			
292 H	**40½**	**44½**	49½	56	61½	67½	72½	78†	84	89½	97½	105½	115	123½	134	143½	156	[167]	177†	167	177½	188½	**199**	**207**
Ration A.																								
299 G	**52**	**59½**	66	73	**80**	**86½**	**93**	**101½**	**111**	124	**129**	**141½**	**149**	160	**168½**	**175½**	**181½**	**[190]**	**197**	**194**	**183**	{N.W.	**198**	210}
																					Carotene therapy			
Ration B, 4 % $CaCO_3$.																								
291 G	**42**	**45½**	50	**56½**	62	68	**74½**	83	89	**97½**	104	**105½**	**114**	**117½**	**123**	**126**	**136**	**[144]**	**148**	**157½**	**153**	{**161**	**170**	**182**}
																					Carotene therapy			
296 H	**40**	**44½**	**49**	**54**	**60½**	**64½**	69	**76**	82	**89½**	**97½**	**101½**	**107**	[108]	**111**	{**119**	**127½**	137½	146	151	161½	170	180}	
																		Cod-liver oil therapy						
289 G	**42½**	**47½**	**52**	60	**66**	**71½**	78	[82½]	**86**	**91**	**85½**	**80**												

Figures in black type denote that animal had not consumed its total food allowance during the previous week.

† Removed from the experiment for 5 days during this period for resting catabolism determinations.

[ ] First marked symptoms of incoordination of movement.

H = hog; G = gilt.

N.W. = Not weighed owing to condition.

gradually resumed a straight gait. Normal growth was obtained at a much earlier date than a normal clinical condition. Within 5 weeks, however, with the exception of the animal referred to above, which recovered more slowly, there was no apparent difference physiologically or clinically between the diseased animals and the controls. At this time we were unable to explain the apparently anomalous nature of the reaction of the animals to the vitamin supplements.

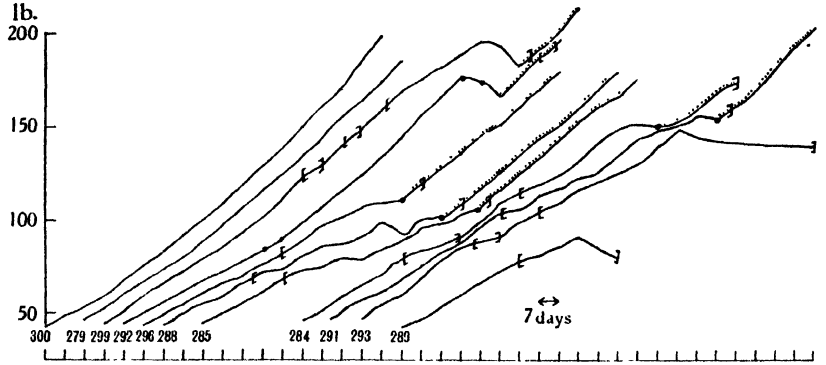


Fig. 1. Graph showing the live-weight increase of the animals.

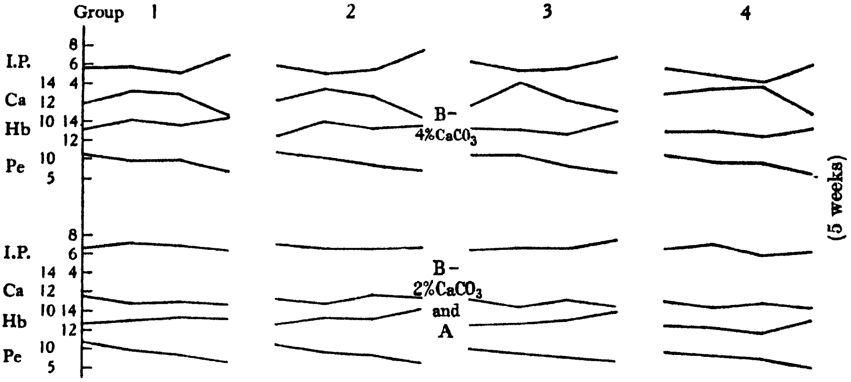
——— basal ration only.
...... basal ration plus vitamin supplement.
• curative treatment commenced.
[ ] animal adopting a plane of nutrition lower than that imposed.
300, animal making fastest gain on ration A or B, 2 % $CaCO_3$ in groups 1, 2 or 3.
279, animal making slowest gain as above.
284 and 285, orange-juice therapy.
288 and 296, cod-liver oil therapy.
291 and 299, carotene therapy.
289 and 293, controls.
292, withdrawn from experiment at points shown for resting catabolism studies which necessitated complete starvation over a period of 5 days.

Blood analysis.

Routine clinical examination of the blood for serum Ca, inorganic P, haemoglobin, phosphatase and red blood cells had been carried out at 5-weekly intervals on all animals when the disease symptoms appeared. This was continued after the disease symptoms developed. The average results for each group are shown graphically in Fig. 2.

Bone analysis.

The tibia was dissected out from the left hind limb of each animal after slaughter. After drying at 95° C. to free from moisture the bones were allowed to stand under alcohol and then under ether with occasional shaking. When sufficiently fat-free they were ground up in an electric mill and re-extracted with alcohol and ether in a Soxhlet apparatus. After drying off the ether the ash content of the fat-free bone was determined on a 5 gm. sample. The following are the average results:



Fig, 2.

I.P. = blood inorganic phosphate mg. per 100 ml.
Ca = serum calcium mg. per 100 ml.
Hb = blood haemoglobin gm. per 100 ml.
Pe = phosphatase units per 100 ml. (Bodansky).

	Group			
Ration	1	2	3	4
B, 4 % $CaCO_3$	56·4	56·3	55·7	55·3
B, 2 % $CaCO_3$	57·8	57·6	57·1	56·9
A	57·0	57·4	56·1	56·5

Liver analysis.

The vitamin A content of the livers was kindly assayed by Mr A. Davies, using his new antimony trichloride method (2). The results are expressed in blue units per gm. according to Moore's system (3) and are given in Table III.

Vitamin A potency of the experimental rations.

Samples of the various foodstuffs comprising the basal rations were analysed by chemical methods to determine their vitamin A potency. Barley meal, oats, wheat middlings and soya-bean meal being plant products contain no vitamin A as such, and their contribution to the vitamin A activity of the ration depends on the presence and abundance of the lipochrome—carotene. Fish meal on the other hand, being an animal product, may contain certain amounts of vitamin A as well as carotene, and it is necessary therefore to estimate both these constituents to arrive at an accurate measure of the total activity.

Table III. *Blue value of livers of animals when slaughtered.*

Weeks after weaning	Group			
	1 L.L.	2 L.O.	3 O.L.	4 O.O.
18	200	37·5	100	0*
	500	0	200	—
	—	17·5	250	—
	—	—	250	—
	—	—	250	—
22	62·5	0	20	0
	—	—	37·5	0†
	—	—	10	—

Vitamin A deficient animals after 2 months C.L.O. therapy [5 ml. C.L.O. per day—625 blue units per gm.] ... 10, 10.

,, deficient animals after 2 months orange-juice therapy [40 ml. per 100 lb. live weight per day—2 yellow units per c.c.] ... 0, 0.

,, deficient animal after 2 months carotene therapy [10 mg. of crystalline carotene per day] ... 20.

* At 14 weeks. † At 26 weeks.

The carotene estimation was carried out as follows. About 150 gm. of the finely ground foodstuff (weighed correct to 0·5 gm.) were extracted for 6 hours in a Soxhlet apparatus with methylated ether. At the end of this time the ether invariably siphoned over perfectly clear. The extract was centrifuged for 4 min. at 3500 r.p.m. to clarify and then freed from ether under diminished pressure at room temperature. Alcoholic potash, prepared according to the directions of Burr and Burr, was added in correct amount to the extract in an Erlenmeyer flask and refluxed for 1 hour on a steam bath. The whole was then transferred to a separatory funnel along with a suitable volume of distilled water and extracted with small quantities of ether (sp. gr. 0·730) till the ether layer separated clear. The combined ether extracts were then washed twice with distilled water and evaporated almost to dryness in a vacuum distilling flask at room temperature. The residue was taken up in 50 ml. petroleum ether to get a light yellow colour and transferred to a separatory funnel. The petroleum-ether solution was then extracted with 50 ml. of 93 per cent. methyl alcohol. After separation of the layers the carotene in the petroleum ether phase was estimated by the method of Willstätter and Stoll (4) using a Bausch and Lomb colorimeter. The table given by Morrow (5) showing the relations between the standard dichromate solution and the carotenoids was used in calculating the carotene content of the solutions.

The method used for estimating the vitamin A content of fish meal was essentially similar to that employed in estimating the blue values of the liver samples. 150 gm. of the foodstuff were extracted with ether in a Soxhlet apparatus and, after clarifying, the extract was rendered ether-free under diminished pressure. Saponification was carried out in a conical flask using aqueous KOH. The further details of the method are similar to those in the procedure adopted by Davies for estimating vitamin A by the antimony trichloride reagent (2).

The results are given in Table IV.

Table IV. *Carotene and vitamin A content of foodstuffs.*

	γ carotene per gm.	Mg. per lb.	Mg. per 100 lb.	Vitamin A b.u. per gm.
Barley meal	0·50	0·22	22·65	—
Oats	0·32	0·14	14·50	—
White sharps	0·08	0·04	3·62	—
Fish meal	0·10	0·05	4·53	Nil
Soya-bean meal	0·13	0·06	5·89	—
Wheat middlings		Not analysed		
Orange juice (unfiltered)	0·89	0·40	40·23	—
Cod-liver oil	—	—	—	625

Discussion of the results.

The figures obtained for growth rate in groups 1, 2 and 3 are uniform and consistent. The animals in group 4, however, show a great amount of variation. Actually the results are not strictly comparable with the other groups since the appetites of group 4 animals decreased and consequently their food intakes were not normal. The growth rates are similar, however, to those of the animals in the other groups during the period over which they assumed the same plane of nutrition (Table II). The variation is due to (1) the different live weights which the animals reached before they refused to eat part of their daily allowance of food, and (2) the length of time they continued on the sub-normal planes of nutrition before ceasing to grow in live weight.

When the figures given for blue values of the livers (Table III) are considered in conjunction with the figures given for growth rate, the correlation between presence of vitamin A and normal growth is apparent. The two negative values obtained for animals in group 2 which had normal growth rates confirm the findings of Busson (6) that absence of vitamin A from the liver does not necessarily indicate a state of actual deficiency. The same worker, however, found that its presence in the liver indicated an excess in the organism, and the amount of vitamin A in the liver could be taken as a criterion of the size of the reserves. On the other hand the consistent negative values which were obtained for the livers of animals in group 4 when considered along with their growth curves can only be interpreted as a deficiency of vitamin A.

The blue values of the livers of the animals are of some interest in themselves. Six animals in the experiment were slaughtered 17 weeks after weaning and their livers were not obtained for analysis. Of the three animals which remained in group 1, one animal showed a higher blue value at 18 weeks after weaning than did any animal in the other groups. This is to be expected from the nature of the treatments. Group 2, from which the vitamin A supplement had been withdrawn at weaning, showed very low blue values. Group 3 had low blue values. These, however, were comparatively uniform and were all higher than those in group 2. The liver obtained from the animal killed in group 4 at this stage and which showed marked symptoms of the disease gave a negative value to the colour test.

The large fall in the blue values of groups 1, 2 and 3 when the livers of animals were analysed 4 weeks later, shows beyond doubt that the basal rations were deficient in vitamin A for the proper nutrition of swine. It is interesting to note that at this stage the values obtained for group 3 agree with those obtained for group 2, 4 weeks previously. This finding can be correlated with the group treatments, since group 3 received their supply of vitamin supplement 4 weeks later in life than group 2.

It is also interesting to note from the general trend of the results that the vitamin A reserves of the animals in group 2 must be exhausted—or almost so—at 22 weeks from weaning. It is probable that, had the animals in this group been allowed to reach weights of 250 lb., a number of them would have shown symptoms of the disease which affected all animals in group 4.

The storage of vitamin A in the animals receiving curative treatment was also investigated. Analysis of the livers of these animals at slaughter, and analysis of the carotene and vitamin A content of the supplements, showed that the amounts stored in the body were proportional to the amounts present in the supplements. Thus the orange-juice therapy, supplying only small amounts of carotene in the diet of the animals, proved sufficient for recovery from the disease and later for normal growth, but provided no excess for storage in the liver. Recovery from the disease and resumption of normal growth were also obtained by the carotene and cod-liver oil therapy, but the amounts fed provided an excess of vitamin A which was stored in the liver in amounts corresponding with its abundance in the diet.

Blood and bone analysis.

No group differences were obtained in the results for the clinical routine examination of the blood. One animal in group 4 on ration B, 4 per cent. $CaCO_3$, when in an advanced state of the disease showed an extremely high value for serum Ca (16·35 mg. per 100 c.c.) and an extremely low one for blood inorganic P (4·4 mg. per 100 c.c.) which were the most extreme values found. Other animals in this group on the same ration, however, showed values which agreed closely with those obtained for comparable animals in the other groups. Other less marked variations in the blood picture of group 4 animals at this stage could be explained on the basis of their state of semi-starvation which accompanied the symptoms of the disease. The figures obtained on analyses of the bones support the conclusion that the condition of the deficient animals was not due to any upset of their Ca, P and vitamin D metabolism, and that vitamin D has no sparing action on vitamin A.

Vitamin A potency of experimental rations.

One factor influencing the susceptibility of the animals to the disease symptoms appears to be significant. As a result of the experimental technique employed in feeding the animals, a fast-growing animal must necessarily require less food for a fixed gain in weight than an animal which increases in weight more slowly. Thus a fast-growing pig requires about 300 lb. of dry matter for 100 lb. of live-weight increase, while the slow grower may require over 400 lb. It is conceivable therefore that the vitamin A content of the ration may be such that the amount present is insufficient for the former animal but adequate for the latter, since it has 33 per cent. more vitamin A at its disposal for the same gain in weight. In the present experiment, economy of gain appears to have been the chief factor governing the time of onset of the disease symptoms. The time taken for different animals to develop the symptoms can, at least, be accounted for better on this basis than by accepting varying initial vitamin A reserves or abstruse physiological factors as the explanation. This is apparent from the direct relationship obtained between the growth rate of the animals while their food intake was normal and the first signs of incoordination of movement. The two animals with the fastest growth rates were the first to succumb.

Of the ten animals receiving ration B, 4 per cent. $CaCO_3$, No. 289 had the fastest gain in weight from the beginning of the experiment till it began to refuse food. The animal was killed when it was apparent that it must soon die. Of the animals on ration B, 2 per cent. $CaCO_3$, No. 288 was the first to show symptoms. From the start of the experiment its food consumption was variable so that its growth rate is not strictly comparable with the other animals. However, for 24 days previous to the experiment the food consumption of the animals when offered unlimited amounts was recorded, and during this period animal 288 increased in weight from 30 to 51 lb., which was 2½ lb. more than any other group 4 animal. In making this gain of 21 lb. the animal consumed 48 lb. of meal or 2·29 lb. per lb. of live-weight increase. The animal with the next lowest economy of gain required 2·4 lb.

Animal No. 292 was the last animal on ration B to develop the symptoms of the disease. When these appeared the appetite was still normal and food was not refused till its live weight was over 190 lb. The comparatively slow growth of this animal had been noticed from the beginning, and it was decided to investigate the cause of its slow progress. When its live weight was 78 lb. it was withdrawn from the group and placed in a calorimeter to determine the resting katabolism. Between 90 and 177 lb. its growth rate was similar to that of the slow-growing normal animal, No. 279. It was again removed to the calorimeter when 177 lb. in live weight, at which stage it had developed a markedly swaying gait. When it was returned to the experimental pen some 5 days later after having lost 22 lb. (including 7¼ lb. of faeces) the disease symptoms appeared to be more marked. These, however, seemed to improve slightly up to the time the animal was slaughtered, when its live weight was 207 lb.

If the ration is considered to meet the requirements of this animal then vitamin A content of the ration is sufficient for a rate of growth of 1 lb. per day between 40 and 200 lb. with an economy of gain of 4·4 lb. of the ration per lb. of live-weight increase. The ten normal control animals on the same ration made gains of 1·2–1·3 lb. per day between the same weights, while their food consumption records showed an economy of gain of 3·23–3·35 lb. meal per lb. of live-weight increase.

The vitamin A potency of the basal ration B was 12·4 mg. carotene per 100 lb. This amount, however, only provided for a very slow rate of growth as shown by animal No. 292. Of the two deficient animals which received orange-juice supplements the smaller animal recovered on a diet containing the equivalent of 13·4 mg. carotene per 100 lb., while the other in which the symptoms were more severe failed to recover completely when the amount was raised to 14 mg. The animals receiving cod-liver oil and carotene recovered on diets containing the equivalent of 62 mg. and 178 mg. carotene per 100 lb. of the ration, respectively, amounts which allowed for a certain amount of storage in the liver.

From these considerations therefore it is clear that a diet containing 14 mg. carotene per 100 lb. is insufficient for normal growth, while one containing 62 mg. per 100 lb. gives normal growth with storage of the vitamin. Between these amounts lies the necessary vitamin A potency of a diet for normal growth and low economy of gain in swine.

Review of the literature relating to the disease.

A number of workers have already reported observations on a disease in swine in which similar symptoms to those already described in this paper have been found. Hart, Miller and McCollum (7) in 1916 showed that even when skim milk, oil meal or minerals were added singly or together to wheat and grain mixtures, definite symptoms of malnutrition in swine were produced. This was evidenced by staggering gait, loss of power in the forelimbs and degenerative nerve changes in the animals. The authors attributed their results to absence of fat-soluble A, since normal growth was obtained when meat scraps or alfalfa meal were added to the diet. Plimmer (8) reports an actual case under practical conditions of swine husbandry in which like symptoms were evident and the similarity of these symptoms to those characteristic of vitamin C deficiency in guinea-pigs, along with the successful treatment of the condition when the ration of the animals was fed in the uncooked state, led to the conclusion that the animals had developed scurvy. Various workers, however, have since shown that the pig, like the rat, can synthesise vitamin C in its body. In the light of later work, in which similar symptoms to those found by Plimmer have been described, it seems possible that the animals suffered from a deficiency of vitamin A in the diet, which was rectified when he fed the ration uncooked and increased the swede-juice supplement. In 1920 Steenbock and Boutwell (9) published their results, which showed a positive correlation between the occurrence of yellow pigmentation in maize and the growth-promoting property associated with the presence of the fat-soluble vitamin. Almost simultaneously Morrison, Bohstedt and Fargo (10) demonstrated the remarkable difference in growth rate and health when white corn (maize) was substituted for yellow corn in a ration fed to swine and the improvement which resulted when orange-coloured carrots and alfalfa meal were fed as supplements to the white-corn diet. They associated the improvement with the fat-soluble vitamin. In a later paper (11) the same workers showed that animals allowed to develop to 142 lb. on complete rations made as good growth afterwards on white corn as they would on yellow corn. This they considered to be due to vitamin A storage in the livers of the animals. Further studies on the requirement of swine for the fat-soluble vitamin were those presented about the same time by Zilva, Golding, Drummond and Coward (12) and Golding, Zilva, Drummond and Coward (13), who concluded that while the fat-soluble factor promotes growth in pigs fed rations in which the factor is absent, the actual requirement is low. Their work also provided an indication of the dual nature of the fat-soluble vitamin since they report (1922) that "on various occasions during experiment animals displayed a condition described by the practical man as 'off their feet.' This is not necessarily due to rickets. No doubt before now such a condition has been loosely referred to as rickets." Indeed the diet which they used (containing 0·338 per cent. Ca) has since been shown to give normal growth when the vitamin A requirement of the animals has been provided for (13a).

During the following years negative evidence was put forward as to the importance of vitamin A in swine nutrition. Lamb and Evvard (14) in 1923 report experiments in which normal pregnancies and lactations were invariably obtained on a ration containing a large percentage of white corn, which also proved itself equal to yellow corn for growth and fattening. White and Roberts (15), as the result of a single trial consisting of two treatments, state that there must be less danger of pigs suffering from lack of vitamins than is often suggested. Their rations, however, are not given. In 1924 Orr and Crichton (16) showed that the addition of cod-liver oil to a cereal-animal protein diet, which they believed was deficient in vitamin A, did not prove itself superior in growth-promoting properties to the same diet plus linseed oil. All the animals appeared normal throughout the experiment. The authors conclude that the vitamin A requirement of the pig is so low that, during the usual fattening period, there is little likelihood of pigs suffering from vitamin deficiency under practical conditions. They attribute Plimmer's results (8), obtained at the same institute, to lack of minerals (calcium and phosphorus) and assert that the animals recovered from their rachitic condition because they had been turned out of doors to graze and root.

In 1926, however, Rice, Mitchell and Laible (17) demonstrated that pigs have definite need for vitamin A supplements even under practical conditions of swine husbandry. Using the white-corn tankage ration it was shown that the piglings, reared by sows also fed this diet, failed to thrive, developed marked pathological symptoms and died. Pigs, from other sows, raised on normal rations till they reached 60–70 lb: live weight were shown to run out of vitamin A before they reached 200 lb. when fed the experimental ration. Daily supplements of alfalfa meal—1 oz. per head per day—proved sufficient to make good the deficiency of vitamin A in the ration till the animals were slaughtered at 227 lb. live weight. These results when considered in conjunction with those of Morrison, Bohstedt and Fargo seem to explain the negative evidence for the need of vitamin A obtained by the other workers. Thus, in experiment 3 of Orr and Crichton's paper, the animals used were 4 months old before they were fed the experimental rations, during which time they presumably had stored sufficient vitamin A from their previous diet. In their second experiment, in which swede juice was fed in addition to the basal ration to rule out any possible deficiency of vitamin C, it is probable that the amount fed (20 ml. per day) contained appreciable amounts of carotene. Furthermore, blood meal which was included at the 8 per cent. level in their supposedly deficient diet has been shown by Scheunert to contain vitamin A while other animal-protein meals studied contained none (18). The vitamin potency of blood meal appears to be due to carotene which is the principal pigment in blood serum (19).

Bohstedt *et al.* (20) in a discussion of their results do not distinguish clearly between the conditions produced by lack of vitamin A and those which lead to rickets. They obtained evidence, however, for lack of vitamin A in their rations by adding supplements of aerated cod-liver oil which supplied sufficient vitamin D but not A. The malnutrition resulting from this diet was rectified by small additions of alfalfa meal. They conclude that "there is evidence that vitamin A, perhaps indirectly, plays a part in preventing stiffness in pigs."

In 1928 Hughes, Aubel and Leindhart (21), after extended investigations, published an account of their work which, they claim, is the first description of the symptoms and lesions in pigs in an advanced state of avitaminosis A. The symptoms of impaired vision, extreme incoordination of body movements and spasms which the pigs developed were shown to be correlated with degeneration of the spinal cord and sciatic and femoral nerves. Eye lesions were found to be of minor importance contrasted with the picture in rats. These changes are similar to those found by Mellanby who, in a series of papers (22, 23, 24, 25) has published an account of the morbid histology of the disease as it affects dogs. Section of the spinal cord showed shrinkage of the motor cells of the ventro-medial and ventro-lateral columns and crowding of Nissl's granules, along with the near obliteration of the nucleus and nucleolus in the cells and degeneration of the processes. Degenerative changes were also encountered in the optic, sciatic and femoral nerves.

In a later paper Hughes, Leindhardt and Aubel (26) presented a similar picture of the disease in other animals—chickens and cows. The symptoms of impaired vision, incoordination and spasms occurred with the same degree of severity in those animals as in swine. The disease has recently been found to occur among cattle under natural ranching conditions in America during a dry summer (27). The livers of affected cattle were found to be negative to the vitamin A colour test.

Longwell and Weakley have shown in a recent publication (28) that the disease occurs using a mixed ration containing normal amounts of meat meal. Their rations consisted of (1) white corn, oats, linseed meal, tankage and minerals, and (2) white corn, buckwheat middlings, tankage and minerals. These results and our own do not therefore support the conclusion arrived at by Sheehy (29) that "the requirement for vitamin A is so low that except under experimental conditions where the diet is purposely designed to contain as little as possible, there is no danger of a deficiency." In stating later, however, that "either yellow maize, green food or milk given in substantial amounts, will supply all that is necessary," he appears to infer that the requirement is appreciable.

Workers in Copenhagen report an experience similar to our own in which symptoms of the disease occurred in certain experimental animals. They appear to have been unable to offer an explanation for the abnormality, but it is significant that as the tapioca flour replaced the corn in their rations in increasing amounts the symptoms of the disease occurred in their animals with increasing severity (30).

PRACTICAL CONSIDERATIONS.

It may be argued that the conclusions drawn from the experiment cannot be applied to conditions in normal practice on account of the rigid adherence to a definite plane of nutrition for each animal irrespective of its appetite and the peculiar nature of the vitamin supplement supplied to the young animals.

In the first case, however, the old practice of feeding to animals amounts of meal which they will consume within a given time (20–30 min.) is now less common. The grading of carcases has taught feeders that this method of feeding leads to an inferior product. The method now being adopted is to ration the animals according to their live weight and it is being found that the figures given by the late Prof. T. B. Wood are extremely suitable for producing carcases of a high grade. Wood's figures form the basis of the plane of nutrition adopted at this institute. Until recently a slaughterhouse near by received the experimental animals which it was desired to dispose of. At the end of last year, however, ten animals were accepted by a bacon factory and nine of the carcases were awarded grade B. The ration was one which is fairly common in swine husbandry and only 3·3 lb. were required to give 1 lb. increase between 40 lb. and bacon weights. Further work is necessary, however, before the most suitable plane for all breeds can be determined, but the system of rationing finally adopted for Large Whites cannot be far removed from the amounts in Wood's tables.

With regard to the vitamin supplement it is obvious that the healthy animals obtained from raw liver some essential dietary constituent (or constituents) which the basal rations contained in insufficient amounts and which green food supplies under practical conditions of swine husbandry. This, at least, appears to be the only explanation of the normality of the liver-fed animals and, at the same time, to account for the comparative absence of the disease in actual practice when the "official" rations are fed. Apart from vitamin A, the basal ration contains all the necessary dietary constituents for normal growth, since the group 4 animals received no food from any other source after weaning, and crystalline carotene added alone ensured complete recovery from the disease and resumption of normal growth. On these grounds therefore it is clear that the only function of the liver supplement, when fed in conjunction with the ration, was to build up a store of vitamin A within the body, and this would have been accomplished equally well with pasture grass or other green food (31).

Some mention should also be made here of the effect of the nutrition of the sow on the vitamin A reserves of her offspring (1) at birth, and (2) when weaned. The studies of Dann (32) and Moore (33) provide some information on this point, and show conclusively that the vitamin A reserves of the new-born animal are small and fairly constant (25–30 b.u. (Moore's) per gm. of liver) and are unaffected by the amount in the diet or the stores in the liver of the mother at the time of birth. Furthermore, any increase in the vitamin A content of the milk secreted during suckling is small in proportion to an increase in the amount of the vitamin ingested. Thus the mother is unable to exercise any great effect, either via the placenta or via the milk, on the vitamin A reserves of her offspring. The young are therefore dependent on the food they eat to satisfy their requirement for the vitamin.

From these considerations it seems that a point of practical significance arising out of this investigation is that many rations in this country for the nutrition of swine will cause paralysis in the animals especially in cases where low economy of gains is a primary consideration. In farm practice the disease is often referred to as "staggers" or "off their feet." Mr F. Blakemore, of the Animal Pathology Institute, has informed the writer that the disease is common in certain herds. Where the rations used in this investigation are fed alone, the disease will normally develop before the animals are suitable for slaughter. If the animals are allowed to feed on green pasture or if they receive a daily allowance of green stuff in conjunction with the ration before the fattening period commences, the disease should be rare. In those cases in which it does develop under these conditions, either the pasture contains sub-normal amounts of the vitamin (as during the summer of 1933) or the supplementary feeding of green stuff has not been continued for a sufficiently long period of time.

Woodman (34) has shown that the feeding of green stuff as pasture grass is uneconomic for live-weight increase, and from the results of this experiment its only value appears to be that it makes good a deficiency of vitamin A in the "official" rations for swine. The vitamin A requirement of the animal for growth, however, may be provided for by more efficient means, *e.g.* the inclusion in the diet of a foodstuff of high starch equivalent which is also an abundant source of vitamin A. Yellow maize fulfils these conditions. Caution, however, must be practised in its use as it has been shown to have an adverse effect on the quality of the fat in bacon carcases. Other concentrated meals which contain appreciable amounts of vitamin A present similar difficulties. Experiments are now proceeding to discover a fully balanced ration, containing adequate amounts of vitamin A, which is both economical and suitable for normal growth in swine under all conditions of management, and which also gives carcases of high quality for bacon. Analyses of alfalfa meal at this institute shows that it is too variable a product at present to be worthy of consideration. Red-palm oil and, to a less extent, cod-liver oil are rich sources of vitamin A which would partly fulfil the requirements, but their use is uneconomic in swine rations if their functions can be fulfilled equally as well by a foodstuff which is included primarily for its energy content or the biological value of its protein fraction.

SUMMARY.

A description is given of a peculiar condition which developed in certain animals being fed rations at present in use for the nutrition of swine in this country.

The experimental treatments which were being imposed at the time bore no relation to the onset of the symptoms which appeared to develop indiscriminately.

The animals refused food, adopted a swaying or "drunken" gait, at a later stage lost the power of their limbs and finally became prostrate.

Therapeutic treatment was commenced and vitamin supplements of orange-juice, cod liver oil or crystalline carotene gave an immediate response when fed in conjunction with the same ration on which the symptoms of the disease became progressively more marked.

In a remarkably short period of time the animals had regained their appetite for food, the symptoms of the disease diminished in their severity, the power of the limbs was restored and within 5 weeks the affected animals were indistinguishable either physiologically or clinically from other animals which did not develop the disease.

The cause of the condition was found to be a deficiency of vitamin A in the diet. This conclusion was supported by the results of blood and bone analyses, estimations of the vitamin A content of the liver of the animals, and determinations of the carotene and vitamin A content of the foodstuffs and vitamin supplements fed. The vitamin A requirement of swine has been shown to lie between 14 and 62 mg. of carotene per 100 lb. of the ration (90 per cent. D.M.).

A review of the literature shows that the disease has appeared unexpectedly both during experiment and in practice without any adequate explanation being put forward for its occurrence. Recent work also shows that animals are liable to succumb to the disease when many rations of mixed foodstuffs are fed to swine unless precautions are taken to supply an additional source of vitamin A.

The application of the findings to swine under practical conditions of management is discussed.

CONCLUSIONS.

The commonly prescribed rations of (1) barley meal, middlings and fish meal, and (2) cereals, soya-bean meal and minerals are deficient in vitamin A for normal growth in swine and low economy of gains.

When fed these diets swine develop the symptoms of paralysis due to vitamin A deficiency when they reach about 150 lb. live weight or about 14 weeks after weaning.

When a vitamin A concentrate is fed in sufficient amounts during suckling or for a month after weaning, the above rations are suitable for normal growth to bacon weights but provide only a small margin of safety, as the vitamin A reserves are almost exhausted when the animals have received the diets alone for 18 weeks.

By prolonging the period of feeding the vitamin supplement, normal growth is obtained and a greater margin of safety results.

The author takes this opportunity of expressing his indebtedness to Dr T. Moore for advice and criticism. He wishes to thank Dr Leslie J. Harris and Prof. Sir F. Gowland Hopkins for their continued interest during the investigation. His thanks are also due to Mr E. A. Porter who was in charge of the experimental animals.

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AN OPTICAL METHOD FOR MECHANICAL ANALYSIS OF SOILS, ETC.

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(With Eight Text-figures.)

I. Introduction.

THE sedimentation method for the mechanical analysis of poly-disperse systems such as a suspension of soil in water is now in its various modifications a well-established technique of analysis (1). Unfortunately, they all, with one exception, involve interference of some kind with the process of sedimentation itself; either by the introduction of pipettes and hydrometers, or the opening of drain-cocks, and the one exception, viz. the sedimentation balance, is subject to a considerable error of a different kind (2). The present paper describes the results of attempts to use the transmission of a beam of light through a glass cell, as a measure of the sedimentation process taking place within it, the transmitted light being received on a photo-electric cell. The only possible kinds of interference with the process which can take place under these circumstances are two, viz. convection and photo-phoresis. The first is obviated by putting another cell containing water between the source of light and the sedimentation cell, while the latter can only affect particles minute enough to show Brownian motion.

It appears that the idea of measuring the concentration of a suspension by the light transmitted has, up to the present time, been applied only to mono-disperse systems of small particles (3). This is the principle of the "turbidimeter," of which several types are on the market. Further Svedburg and Rinde (4) have examined the settling of a mono-disperse suspension in a centrifuge by observing in a series of photographs the motion of the top of the "cloud" of particles. Proportionality between concentration and extinction coefficient of the light (Beer's law) holds only for particles of "colloidal" size up to a diameter of about $500\mu\mu$ and at small concentrations. For larger particles Teorell (5) has shown that the extinction varies less rapidly than the concentration, but has not found the exact law of the variation. It is obvious that this law must be determined over the average range of particle diameter encountered in soils. It is obvious also that the law in the case of very large particles (*e.g.* a few peas in a jelly), must be that the light cut off is proportional to the projected area. In the case of spherical particles then, the light extinguished must be proportional to some power of the radius between zero (*i.e.* the concentration) for very small particles and the square (*i.e.* the projected area) for large particles. Further, the concentrations in all cases should be small, so that the absorption of light by any one particle is not appreciably affected by its neighbours.

Chéveneau and Audubert (6) in a remarkably exhaustive research have examined the range of particles of diameters comprised between 1 and 10μ, and have found that their results over this range satisfy the law $\log I_1/I_0 = A$, where I_1 is the intensity of the transmitted and I_0 of the incident light, and A depends on n and d directly.

II. CALIBRATION.

To extend this work to larger particles, the present author used a small glass tank which contained a mono-disperse system of known concentration kept from sedimentation by being continually stirred up in turbulent motion by paddles which occupied one side (screened) of the cell. Light from a Pointolite lamp was passed through the whole of the remainder of the tank, and was then concentrated by means of a lens on to the photo-electric cell. The system in the tank consisted of carefully sieved sand or centrifuged gamboge or round seeds of uniform size[1], in each case held in suspension in water.

The results are shown in the following Table. The fifth column gives the total volume (*i.e.* mass/density) of the substance in suspension, which

Table of light extinction results.

Substance	Diameter d (mm.)	Mass m (gm.)	Density ρ	Volume $= m/\rho$ ($v \propto \Sigma nd^3$)	$\frac{v}{d} \propto \Sigma nd^2$	Light cut off $= I_0 - I_1$	$\frac{I_0 - I_1}{\Sigma nd^2}$
Mustard seed in water	2·0	1·0	1·2	0·83	0·415	1·8	4·35
Seeds of *Lychnis alba* in water	1·0	0·85	1·2	0·71	0·7	3·0	4·25
Sand in water	0·5	1·0	2·65	0·38	0·75	3·5	4·65
	0·4	1·0	2·65	0·38	0·95	4·0	4·2
	0·28	1·0	2·65	0·38	1·35	5·5	4·0
	0·25	1·0	2·65	0·38	1·52	6·5	4·3
Lycopodium in water	0·05	0·2	0·8	0·25	5·0	25·0	5·0
Gamboge in alcohol	0·025	0·25	0·86	0·29	11·5	46·0	4·0
Gamboge in alcohol	0·012	0·09	0·86	0·104	8·6	31·0	3·7

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[1] I am indebted to my colleagues, Dr Blackburn and Miss Harrison, of the Botany Department, for selecting suitable seeds.

is proportional to Σnd^3, where n is the number of particles of diameter d; the sixth column v/d therefore represents Σnd^2. In the final column we see that the light extinction, as measured by the photo-electric cell, is proportional to Σnd^2 down to 12μ at any rate.

In Fig. 1 is shown the dependence of the light extinction A on particle size over the usual range considered in soil analysis, plotted in log : log form. The smooth curve is a combination of the three ranges, *i.e.* 1 mm. down to about 0·01 mm., $A \propto d^2$; thence down to 0·001 mm., $A \propto d$; below this, A constant, with the proviso that over this last region A is a function of the wave-length of the light employed. A has been taken arbitrarily as 10 over this region, giving a basis for the purpose of a standard in drawing the figure.

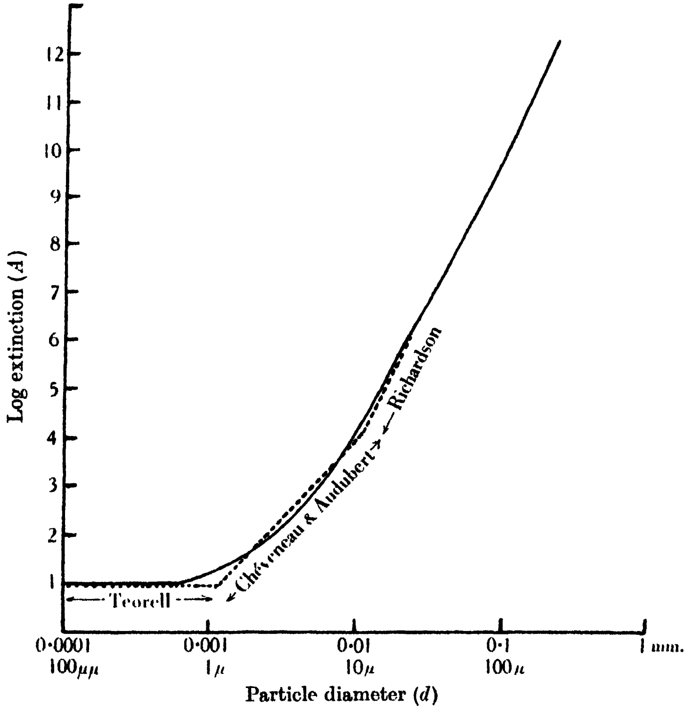

Fig. 1. Calibration of apparatus.

As far as thickness of the suspension, *i.e.* width of cell in the direction of the path of light, was concerned, it was verified that the usual law of absorption of the light was being obeyed, *i.e.* that if I_1 = the intensity transmitted through a thickness x, when the original intensity has been

I_0, then $I_1 = I_0 e^{-kx}$, where k is a constant depending on the nature of the suspension alone.

III. THEORY OF TWO METHODS.

The velocity V of a particle of diameter d and specific gravity ρ falling freely through a liquid of viscosity η, and specific gravity σ, is given by Stokes' law, viz.:

$$V = g\frac{(\rho - \sigma)\,d^2}{18\eta}, \qquad \ldots\ldots(1)$$

or, taking water at 17° C. and of viscosity 0·0105 and soil of specific gravity 1·6:

$$V = 1{\cdot}25 \times 10^4 . d^2 = Cd^2, \qquad \ldots\ldots(2)$$

where C is constant as long as the temperature does not change. Further, if I is the light absorbed by any given layer during sedimentation, we have shown that:

$$I = c\Sigma nd^2, \qquad \ldots\ldots(3)$$

where c is a constant as long as the incident light energy does not change.

To "analyse" the soil we want to obtain the "distribution curve" of n as a function of d. In this particular method it is more convenient to obtain the curve in the form n against d^2. Two procedures are open to us.

(*a*) At a given time t_1 after sedimentation has commenced, we may measure the light extinguished simultaneously over the whole cell, *i.e.* find how I (or Σnd^2) varies with depth y, at time t_1. The light cut off by any layer at depth y' will be due to all particles having velocities $< y'/t_1$ or $d^2 < y'/Ct_1$ by (2), *i.e.*

$$I = c \sum_{d^2=0}^{d^2=y'/Ct_1} nd^2. \qquad \ldots\ldots(4)$$

If now we construct a curve of I against y, the slope of the curve at any value y' of the abscissa will be proportional to the number n of those particles for which $d^2 = y'/Ct_1$.

(*b*) At a given depth y_1, measure at successive times t from the start the light absorbed. The light cut off at a time t' will be due to all particles having velocities $< y_1/t'$, or $d^2 < y_1/Ct'$, *i.e.*

$$I = c \sum_{d^2=0}^{d^2=y_1/Ct'} nd^2 \qquad \ldots\ldots(5).$$

We now construct a curve of I against t, and the slope at any value t' will be proportional to the number n of those particles for which $d^2 = y_1/Ct'$. In each case then, plotting the slope against y (or $1/t$) will give the corresponding distribution curve (after introducing C and either y_1 or t_1 as the case may be) in the form n against d^2.

IV. CONSTANT TIME METHOD (*a*).

A small tank about the size of a photographic quarter plate and 4 cm. from front to back was used, holding 300 c.c. of water to which 1·1 gm. of soil previously washed and passed through a 30-mesh per in. sieve was added. Light from a Pointolite lamp about 2 ft. away passed through the tank and fell directly, without a lens, on the photographic plate behind. This was a plate of normal speed and was exposed for about half a second after sedimentation had been going on for a certain time. Fig. 2 shows the "shadow" of the tank and contents as photographed after (*a*) ½ min., (*b*) ¾ min. of settling. After development the plate was traversed between a source of light and the slit in front of a photo-electric cell, in order that the current passed by the latter, as measured by a galvanometer, should

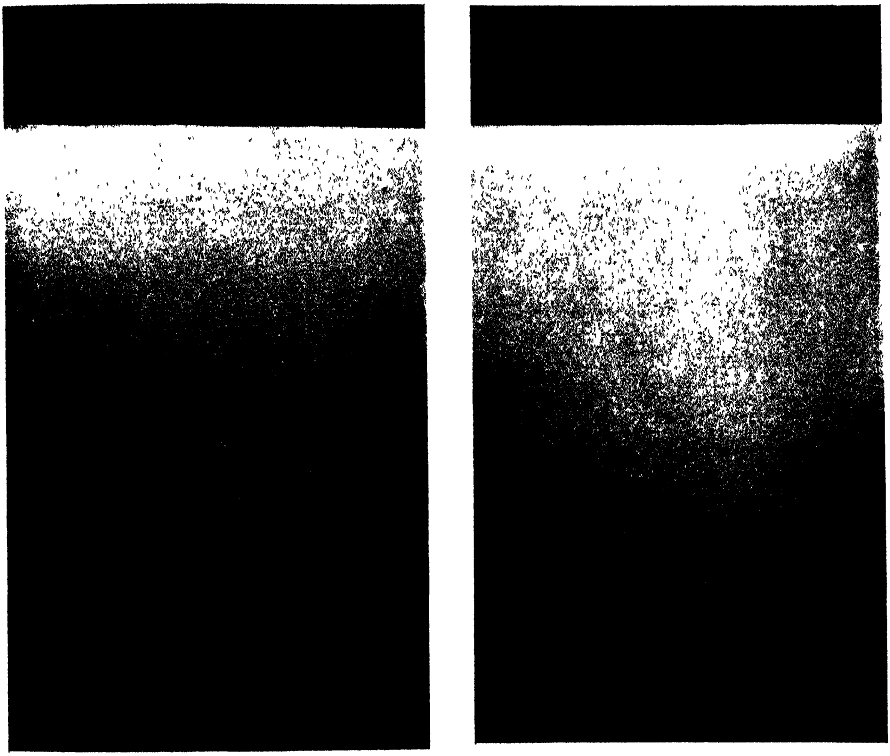

Fig. 2. *a*. Photograph through sedimentation tank after ½ min.
b. Photograph through sedimentation tank after ¾ min.

serve as a measure of the darkening of each part of the plate in turn, and therefore of the light passed by the corresponding level in the tank.[1] The small strip of plate above the water surface was covered by a mask to serve as a reference line and also as a region of "total extinction." The photo-electric cell was of the Osram gas-filled type, run at such a voltage (110) that the current passed by it was proportional to the light falling upon it. The graph of photo-electric current against depth obtained from such analyses of negatives is shown in Fig. 3 for the same soil after three different times of settling, viz. 30 sec., 45 sec. and 60 sec. for total (no absorption) photo-electric currents of 50, 42 and 37·5 units respectively. For a few mm. at either end of the plate the readings are unreliable, that at the top being affected by light scattered from the water surface, and that at the bottom being affected by the accumulated sediment.

V. CONSTANT DEPTH METHOD (*b*).

For this method a tank 25 cm. high was used containing 1 litre of water and about ½ gm. of soil. A narrow beam 3 mm. wide of light from a 50-watt lamp passed through a 2 in. thick water cell (to absorb heat radiations), then through the suspension tank at 15 cm. below the surface on to the photo-electric cell on the other side. A possible source of error, which does not affect the first method, arises here in that the incident light may change in intensity during the long period occupied by a given experiment. A device of the flicker type as used in the turbidimeters of Dobson and Perfect (7) or of Wilson (8) could be used to compensate this, but in the present instance a simple Wheatstone bridge consisting of two photo-cells and two 1000 ohms resistances, with the galvanometer measuring the difference of potential between the junction of the photo-cells and that of the resistances was found to do this satisfactorily, and at the same time to give deflections proportional to the difference of the light intensity received by the two cells.

The latter were placed at equal distances on either side of the source, the compensation beam passing through a pure water cell of equivalent thickness. Fig. 4 shows the resulting curve for the same soil as that used in the first method, in two forms, viz. absorption against time, and absorption against limiting velocity = 15 cm./time. The latter curve has the same general shape as those of Fig. 3. The cells were stirred vigorously by a mechanical paddle to produce dispersion, and at a given instant the paddle was removed and sedimentation started.

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[1] The proportionality between the darkening of the plate and the light intensity, was tested by a separate experiment.

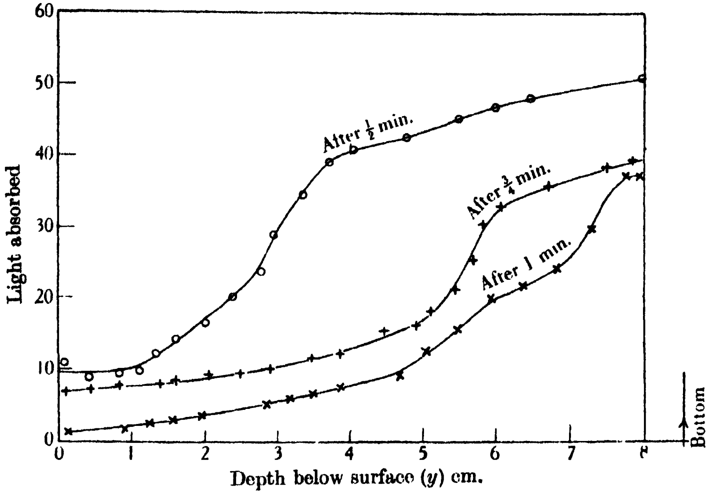

Fig. 3. Results of constant time method.

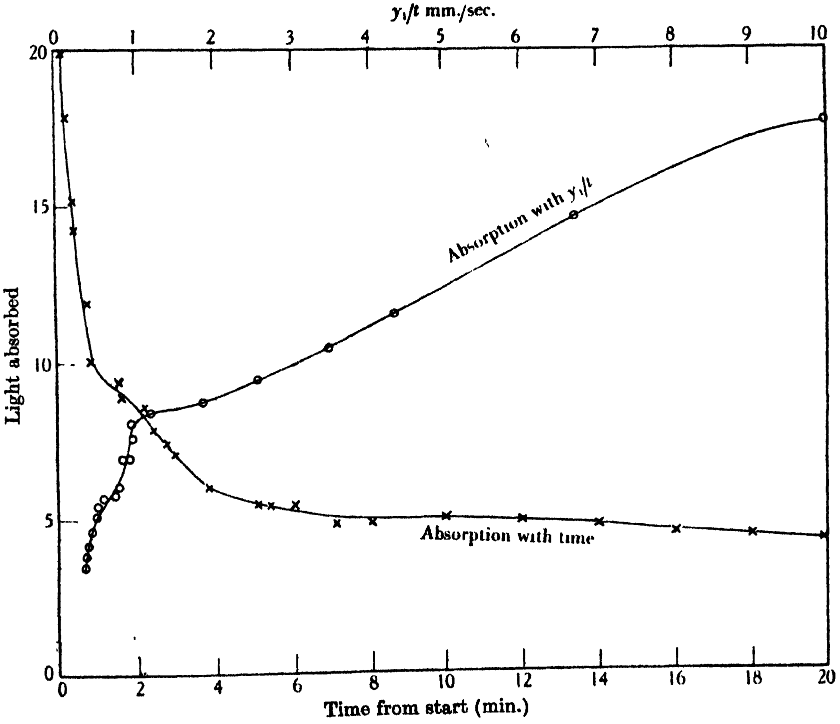

Fig. 4. Results of constant depth method.

This method has further the advantage that it may be made to record automatically, if the deflection of the galvanometer be photographed on a moving sensitised strip. The author has used a string galvanometer in place of the usual moving-coil type, the motion of the string being recorded on a bromide paper strip moving slowly round on a drum driven by clockwork in a light-tight box. Many laboratories may not however possess this rather expensive item of equipment. In this case a critically damped moving-coil galvanometer will serve equally well provided a correction is made for the lag in the movement when the suspension-density is varying rapidly. Fig. 5 for instance gives a continuous record for the first ten minutes of the test soil, which does not need an appreciable correction, but Fig. 6 for a rapidly settling suspension of sand (density 2·65 gm. c.c.) in a mixture of glycerine and water (density 1·15 gm. c.c., viscosity 0·068 cm. gm./sec.) at 20° C. will illustrate the method of correction. It is similar to that used by Einthoven (9) for his string galvanometer. The photo-electric cell, being in the dark, is suddenly exposed to a constant illumination—in this case, to the light passing through the vigorously stirred suspension (*A* on the record). Instead of indicating a sudden rise in current to a steady value (path *ABFC*), the galvanometer deflects slowly (path *ADC*). At *C* the stirring is stopped and rapid settling begins. We compare the slope at any point on the sub-

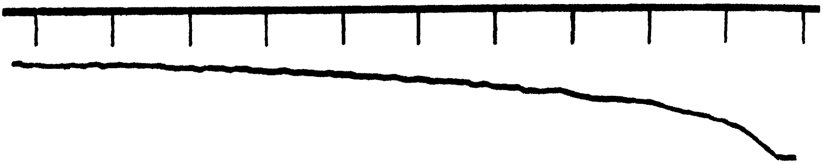

Fig. 5. Continuous record of settling soil. (Vertical lines are at 1 min. intervals. Horizontal straight line represents light passed by clear water.) (*Read from right to left.*)

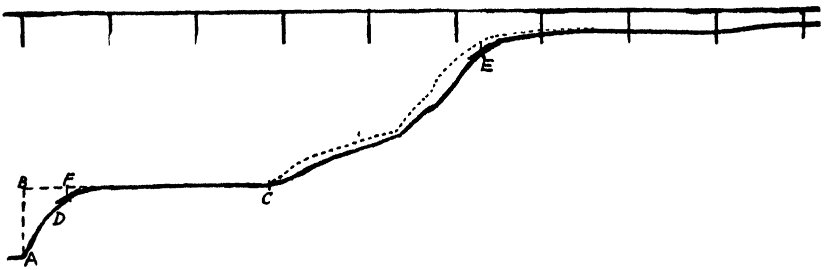

Fig. 6. Continuous record of settling sand. (Vertical lines are at 5 sec. intervals. Horizontal straight line represents light passed by clear water.) (*Read from left to right.*)

sequent curve, *e.g.* E, with the point D on the first curve which has the same slope. The true reading, in the absence of damping, corresponding to D is F. We add DF then to the deflection at E and get a point on the corrected curve of settling. The complete corrected curve is shown as a dotted line. The horizontal straight lines on these figures show the current in the absence of absorption, viz. the intensity of the incident light.

VI. SUMMARY AND GENERAL NOTES ON THE OPTICAL METHOD.

If a comparison is to be made between the new method and the present methods, the Oden sedimentation balance seems the most useful apparatus for comparison purposes since it can also be made continuous or automatically recording (10). Coutts and Crowther (2) have pointed out, however, that the sedimentation balance suffers from a serious defect. The sediment is collected in a scale pan, consequently the liquid below the scale pan becomes less dense, setting up currents in the neighbourhood which seriously perturb the indications of the instrument. The author set up a simple sedimentation balance in which the trouble was obviated to a certain extent by providing the pan with a rim below[1], pierced by a few holes to let out entrapped air. This reduces the convection currents, but still tends to promote a lower density of the fluid below

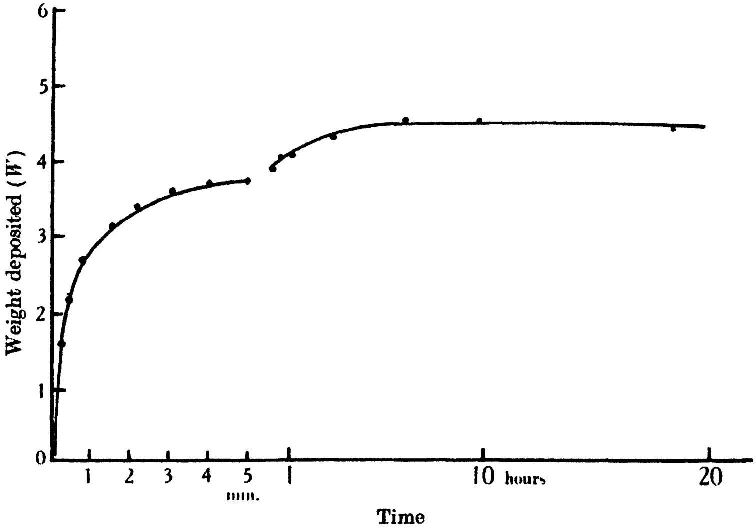

Fig. 7. Sedimentation balance method.

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[1] A suggestion of Mr D. G. Murdoch, put forward at the Discussion of the paper of Coutts and Crowther (2).

the pan as time goes on. The pan being surrounded by a suspension of the experimental soil (10 gm. in 1 litre), the increase of weight of the pan was measured from time to time by shifting a rider which bestrode the balance beam. The resulting weight : time curve at 15 cm. depth is plotted on Fig. 7. To find the distribution curve from this, we have to calculate t^2dW/dt (1), or we may draw tangents at a number of points and measure the difference of their intercepts on the axis of W (4). This is plotted, together with the slopes of curves relating to the optical methods (Figs. 3, 4), to give the distribution curves of Fig. 8 which shows the substantial agreement between the three methods. Graphical measurement of the tangents to the curves was adopted. With regard to the curve (A)—constant time method—a certain amount of judgment must be exercised with regard to the curve whose slope at a given depth shall be regarded as most reliable. For reasons given earlier, measurements referring to the middle of the cell should have greater weight attached to them than those near either end. This has been done in drawing Fig. 8. If one relied on a single photograph for each specimen of soil, the agreement with results by other methods would not be so good. Similar remarks apply to the choice of a suitable time in the constant depth method, though to a less extent, since the water tank was taller. It would be an advantage to use a taller tank in the former method, although this would

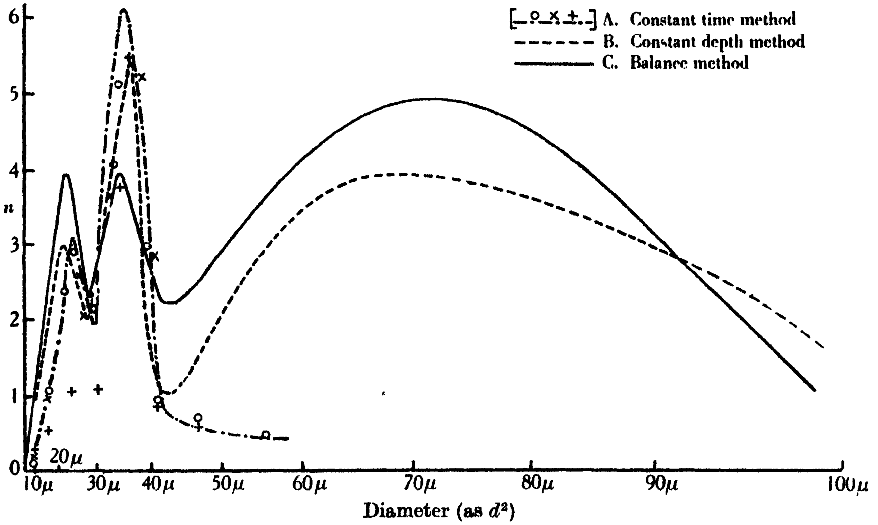

Fig. 8. Combined distribution curves of soil. (The circles and crosses refer to the corresponding curves of Fig. 3.)

entail the removal of the source of light to a greater distance, in order to avoid oblique rays, and this again would require a more intense source. All curves with this soil specimen, however, show inflections at the appropriate places, which are the causes of the troughs in the distribution curves in the neighbourhood of 30μ and 40μ respectively.

The practical advantages of the optical method should be sufficiently clear from what has already been written to make reiteration unnecessary. Perhaps the greatest defect that it possesses is the fact that the Σnd^2 law is admittedly a generalisation, and fails for the smallest particles, *e.g.* those of diameter less than 10μ. A correction could, however, be applied to the corresponding parts of the light absorption curves, having regard to Fig. 1. Below a limiting velocity of 1/120 cm./sec. ($d=10\mu$) the absorption readings could be progressively reduced in the ratio of $d/10\mu$. The 5μ particles for example give twice the absorption which they would if the Σnd^2 law were obeyed by them. Such a correction would not affect the slope of the parts of the curve corresponding to higher velocities, but would give rise to corrected slopes for the smaller particles. It would also be necessary to work with a source of light of limited wave-length, *e.g.* a mercury lamp, if such small particles were to be reckoned. It is of course understood that the soil is washed clear of all soluble salts which might produce a coloured solution, before the optical method is applied.

If one is going to demand great accuracy in mechanical analysis one ought to raise the whole question of the validity of the sedimentation method of mechanical analysis. This has already been considered in detail by Lunnon (11) and Needham (12) in connection with the analysis of mineral ores. Undoubtedly, recent work has shown that Stokes' law is valid for a more limited range of Reynolds' numbers than was formerly believed. Schiller and Naumann (13) have very recently published useful tables from which the terminal velocity of a particle of given radius can be calculated as a function of Reynolds' number. The resistance begins to deviate from Stokes' law (proportionality to velocity) at a value of the latter factor of about 3, which, for soil settling in water at 20° C. means a particle diameter of $d=0{\cdot}2$ mm. ($V=3$ cm./sec.). The tables are given in general form to enable them to be adapted to a solid of any specific gravity in a liquid of any specific gravity and viscosity, so that calculation would be rather tedious if the tables were to be applied in their present form to the settling of soil in water, but they could readily be simplified for agricultural purposes and expressed as a correction to the amount of the larger particles recorded. Another optical correction of the type indicated above could be applied at the other extreme to the colloidal particles. Even if such corrections were not attempted, a distribution curve of the type of Fig. 8 would still be valid over the greater part of the particle range.

The mechanical analysis of soil is not the only process to which these optical methods can be applied. The sampling of mineral ores, the analysis and measurement of dust in the air in mines and of the sediment carried in suspension by rivers are other subjects which suggest themselves, and to which it is hoped to apply these methods.

I wish to express my thanks to two undergraduate students, Messrs H. Gray and R. G. Sayer, for their assistance in taking the observations.

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THE FUNGICIDAL PROPERTIES OF CERTAIN SPRAY-FLUIDS, XI.

SYNTHETIC SOLVENTS.

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Preliminary work on the search for substitutes for sulphur and the sulphur-containing sprays for the control of powdery mildews (Erysiphaceae) is described in Part VIII of this series (10). To the reasons there given for this investigation may be added the undesirability of applying sulphur as a fungicide to fruit or vegetables intended for canning. The materials examined in the experiments there described were chosen on account of their suitability as solvents for contact insecticides such as nicotine, pyrethrum extract or rotenone, and they were confined to oils derived from natural sources, *e.g.* tar and petroleum oils or glyceride oils. At the same time, spray trials were carried out using manufactured solvents of which a large range are now commercially available at prices which do not prohibit their use as spray materials. These products have the great advantage over such solvents as the tar and petroleum oils that, in many cases, their standardisation by chemical analysis is simple. This work has been continued as biological material became available and, although a rigid systematic investigation was not adhered to, it is possible to classify, on chemical lines, the materials tested under the following heads: (1) Hydrocarbons, (2) Hydroxyl-derivatives, (3) Esters.

For preliminary work, ordinary commercial samples of these materials were used, and only when interesting results had been obtained with this grade were they purified or otherwise subjected to analytical control. Particulars of the preparation of the sprays are given below under the separate headings, but in all cases where emulsification or the addition of a spreader was found necessary the same material was used, namely, 0·25 per cent. Agral I, a proprietary spreader of which the sulphonates of cyclic hydrocarbons containing aliphatic side-chains are declared to be the active ingredients. In other cases the emulsifier or spreader used was a dilute soap solution prepared by the addition of oleic acid (to give 0·10 per cent.) to 0·03 per cent. sodium hydroxide.

The fungicidal properties of the sprays were tested upon the conidial stage of the hop powdery mildew (*Sphaerotheca humuli* (DC.) Burr.) growing on the young leaves of hop plants in an unheated greenhouse. For the preliminary experiments any young leaf bearing suitable patches of the fungus was used, but, for the more exact work, only leaves of rooted cuttings of clone-plants (Ref. No. B18) were used. Further, when a comparison of the action of two sprays was required, pairs of leaves at the same node were selected, one spray being applied to one, the second spray to the other leaf of each pair. By this means, the behaviour of the sprays under similar biological and external conditions was compared.

In the tables following, in the column recording the action of the spray-fluid, the letter F. has been used to designate complete fungicidal action, *i.e.* the death of all powdery patches of mildew; S.F. super-fungicidal, *i.e.* fungicidal not only for the patches of mildew in the "powdery" conidial stage, but also for the younger, pre-powdery "hump" stage, which has been shown ((5), p. 286) to survive a concentration of certain polysulphide washes which is lethal to the "powdery" stage; N.Q.F. a not quite fungicidal action—the mildew although greatly checked, survives and produces a small number of conidiophores with conidia; N.F. non-fungicidal, with no observable checking action on the mildew patches, which reform densely clustered conidiophores within a few days after the application of the spray-fluid.

(1) HYDROCARBONS.

The commercial solvents which, chemically, are hydrocarbons fall into two groups: the first, those derived by the hydrogenation of aromatic hydrocarbons, the second, terpenes and their derivatives derived by distillation as essential oils or by synthetic methods.

The first group comprised benzene, cyclohexane, methyl cyclohexane and dekalin. The emulsions produced by agitation of these products with 0·25 per cent. Agral I solution were fairly stable and would be suitable as sprays given efficient agitation in the spray tank. In all cases it was observed that, during the application of the emulsion, the oil separated rapidly and, wetting the leaf surface, caused the final drops of the spray to run into globules. It is convenient to describe this type of wetting as "oily" wetting in contradistinction to the normal wetting of the leaf by the aqueous phase, characterised by the non-formation of drops on the leaf surface once it has been wetted.

The results of spray trials with these compounds are summarised in

Table I.

No. of Exp.	Material	Concentrate tested %	Fungicidal properties	Action on leaf
25 (*bis*)/31	Benzene	1	N.Q.F.	Slight injury on 1 leaf (of 3 sprayed)
158/31	,,	1·5	F. for older, N.Q.F. for younger, patches	No injury
239/31	,,	2·0	N.F.	,,
42/32	,,	2·0	F.†	More or less serious "scorching," often at margin
276/31	Cyclohexane	6·0	N.Q.F. to N.F.	No injury
10/32	,,	8·0	F.‡	More or less serious "scorching" on all the 6 leaves sprayed
32/32	,,	7·0	F., with blackening of patches	Distinct injury, usually at edge of leaf
275/31	Methyl cyclohexane	6·0	N.F.	No injury
121/32	,,	7·0	F.	Distinct injury, usually at edge of leaf
29/32	,,	8·0	F.	Distinct, thought slight, injury
273/31	Dekalin	3·0	N.F.	Slight injury at tip of 1 of the 8 leaves sprayed
33/32	,,	3·5	N.Q.F.	More or less serious "scorching," often at edge of leaf
22/32	,,	4·0		

† By the tenth day some conidiophores had developed from the "hump-stage," *i.e.* the younger, pre-powdery stage of the mildew which has been shown ((5), p. 286) to survive a concentration of certain polysulphide washes which is lethal for the "powdery" stage.

‡ By the second or fourth day all the patches could be seen to have been killed, being more or less blackened and "picked out."

Table I. No attempt was made to investigate the reasons for the different reactions shown in Exps. 239/31 and 42/32, for it was apparent that benzene is able, under certain conditions, to cause severe leaf injury at the lowest concentration lethal to the fungus. Conversion of benzene to cyclohexane has resulted in a reduction of fungicidal and phytocidal properties, possibly associated with the loss of aromatic properties following hydrogenation. The correlation of foliage-injuring properties and aromatic character has already been illustrated by examples, given in Part VIII of this series (10), from the tar and petroleum oils and from the hydrogenation products of naphthalene. In that paper trials are recorded of dekalin which, at 2 per cent., with 0·5 per cent. Agral I, was non-fungicidal and non-injurious. The results of further trials, given in Table I, indicate that dekalin causes leaf injury at 3 per cent., but, as with cyclohexane and methyl cyclohexane, it would appear that these hydrogenation products are free from fungicidal and phytocidal properties at concentrations, *e.g.* 1 per cent., likely to be applied in the event of their use as solvents for the preparation of spray-fluids.

The second group of hydrocarbons examined, the terpenes, are of widespread use as solvents, but, with the exception of turpentine and the pine oils, they do not appear to have been tried as spray solvents.

Cymene, *p*-methyl-*iso*-propyl benzene, of technical quality and of sp.gr. 0·864 (15° C.) was included, as it represents a transitional stage between the aromatic hydrocarbons and the terpenes proper. Carvene and phellandrene were included as typical mono-cyclic terpenes with a technical sample of dipentene, of boiling range 175–185° C., of sp.gr. 0·850 and flash point 130° F., as a cheap commercial representative. Of the bicyclic terpenes only pinene was examined, turpentine of "Best American" quality being used as the cheap commercial representative.

In connection with the possible use of fungicides of the products obtained by the distillation of resins, experiments were also made with a proprietary product, "Soluble Palustrex B." On analysis (9), this material yielded 41·0 per cent. by weight of pine oil, 4·1 per cent. phenols, 37·7 per cent. resin acids and 1·568 per cent. copper oxide. This analysis agrees well with the declared composition of the material, *i.e.* 15 per cent. copper resinate dissolved in "Palustrex," a special grade of pine oil. The resin acids present in excess of the amount required to give copper resinate are apparently present as alkali resinate which functions as the emulsifier. For the trials recorded below the neutral pine oil alone was used. This oil, of boiling range 10 per cent. by volume

Table II.

No. of Exp.	Material	Concentrate %	Adjuvant	Emulsification	Wetting properties	Fungicidal properties	Action on leaf
1/32	Cymene	2	0·25% Agral I	Fair	Oily	F.	More or less serious injury
70/32	,,	1	,,	,,	,,		
101/32	,,	0·5	,,	,,	,,	F., or rarely N.Q.F.	,, ,,
116/32	,,	0·25	,,	,,	,,	N.Q.F.	Occasionally slight injury to tip of leaf
192/32	,,	0·25	0·13% Na oleate	,,	Normal	N.F., with practically no observable action	No injury
203/32	,,	0·5	,,	,,	,,		
84/33	,,	0·5	0·25% Agral I	,,	Oily	F. or N.Q.F.*	,,
85/33	,,	0·5	0·13% Na oleate	,,	Normal	N.F.*	,,
92/32	Carvene	1·0	0·25% Agral I	,,	Oily	F.	Distinct injury to edge of leaf
122/32	,,	0·5	,,	,,	,,	N.Q.F.	Occasional slight injury to tip of leaf
195/32	,,	1·0	0·13% Na oleate	,,	Normal	N.F.	No injury
94/32	Phellandrene	1·0	0·25% Agral I	,,	Oily	F.	Slight or severe injury
128/32	,,	0·5	,,	,,	,,	N.Q.F.	Some amount of injury
3/32	Dipentene	2·0	,,	,,	,,	F.	More or less serious injury
72/32	,,	1·0	,,	,,	,,	F., or occasionally just breaking down	,, ,,
107/32	,,	0·5	,,	,,	,,	F.	Slight injury to edges of 4 of the 5 leaves sprayed
189/32	,,	0·25	,,	,,	,,	N.F., all patches powdery again by seventh day	No injury
74/32	Pinene	1·0	,,	,,	,,	F., or rarely N.Q.F.	Serious injury on 6 of the 7 leaves sprayed
13/32	Turpentine	2·0	,,	Stable	Normal	F.	More or less serious injury to edge of leaf
34/32	,,	1·0	,,	,,	,,	N.Q.F.	Slight or serious injury to edge of leaf
14/32	Pine oil	2·0	,,	,,	,,	F.	Serious injury, usually at edge of leaf
100/32	,,	1·0	,,	,,	,,	F.	Slight or serious injury at edge of leaf
186/32	,,	0·5	,,	,,	,,	N.F., with slight checking action at first	No injury
93/32	Geraniol	1·0	,,	,,	,,	—	Toxic to leaf
109/32	,,	0·25	,,	,,	,,	N.F.	No injury
139/32	,,	0·4	,,	,,	,,	F., or very rarely N.Q.F.†	Slight injury at tip or edge of 3 of the 6 leaves sprayed
15/33	Eucalyptus oil	1·0	0·25% Agral I	,,	,,	N.F., with some checking action at first	No injury
53/33	,,	2·0	,,	,,	,,	F., or occasionally N.Q.F.	Very slight "scorching" injury on 4 of the 6 leaves sprayed
12/33	"Lypticide"	1·25	None	Good	,,	N.F., no observable action	Possibly slight injury
4/32	Fenchone	2·0	0·25% Agral I	Stable	,,	F.	More or less serious injury
95/32	,,	1·0	,,	,,	,,	F., or occasionally N.Q.F.	Slight injury to tips of 3 of the 6 leaves sprayed
191/32	,,	1·5	0·13% Na oleate	,,	,,	N.F., with some checking action at first	Occasional injury to tip of leaf

* Four leaves were sprayed and the corresponding leaves at the same nodes with 0·5 per cent. cymene and 0·13 per cent. sodium oleate.

† A marked "cleansing" action was shown, most of the mildew patches being removed.

at 161° C., 50 per cent. at 180° C. and 80 per cent. at 236° C., readily emulsified when shaken with the dilute Agral I solution.

Certain of the oxy-derivatives of the terpenes were also tested, these included geraniol, eucalyptus oil and fenchone. Eucalyptus oil (B.P.) contains as the predominant constituent cineole which, although an oxy-derivative, has neither alcoholic nor ketonic properties and is regarded as an internal anhydride. Fungicidal properties have been claimed for eucalyptus oil by the makers of the proprietary preparation "Lypticide" which is recommended for the control of certain powdery mildews. Analysis of a sample of this preparation showed it to contain 8·20 per cent. by weight of a terpene-like oil, 10·06 per cent. fatty acids and 0·23 per cent. phenols.

Fenchone, a ketonic derivative isomeric with camphor, was included as a commercial grade of the following specification: boiling range 190–200° C., sp.gr. 0·938, flash point 136° C., ketone content 75 per cent. (approx.), remainder chiefly terpineol, is now available at a price which makes its use as a spray ingredient an economic possibility.

The results of the trials with these derivatives are summarised in Table II, in which the type of emulsion produced and the mode of wetting of the leaf are included. It was observed that the hydrocarbons, with the exception of turpentine and pine oil, yielded unstable emulsions with 0·25 per cent. Agral I which gave "oily" wetting, whereas turpentine, pine oil and the oxy-derivatives gave normal wetting. In view of the marked influence which the type of emulsification may exert on fungicidal properties, as was shown in the vegetable oil trials (11), experiments were also made with soap emulsions, the required amount of solvent being shaken with 0·13 per cent. sodium oleate solutions. The results with cymene afford another illustration of the influence exerted by type of emulsification on fungicidal properties.

As a group the terpenes examined are closely similar in their spray properties. All have pronounced activity, but, under the conditions of the experiments, the foliage damage which they cause prevents the utilisation of their fungicidal properties. A similar conclusion may be drawn regarding the oxy-derivatives examined.

(2) HYDROXYL-DERIVATIVES.

The hydroxyl-derivatives of the hydrocarbons examined fall into two groups: (*a*) alcohols, the hydroxy-derivatives of aliphatic hydrocarbons, (*b*) phenols, derivatives of the aromatic hydrocarbons in which the hydroxyl-groups are directly attached to the benzene nucleus.

(*a*) *Alcohols.*

These mono-hydroxy-derivatives are among the most important of the solvents and already find use as spray ingredients, *e.g.* for the preparation of pyrethrum sprays. The lower members, the use of which may be prejudiced by excise restrictions, were included on account of scientific interest. In trials with low concentrations no action of the spray on fungus or leaf was observed and, at the high concentrations given in Table III, the wetting properties of the solution were sufficient to render the use of an additional spreader unnecessary. The sample of methyl alcohol used was a commercial duty-free sample, that of ethyl alcohol was an undenatured sample of 68 O.P. Pure Kahlbaum samples of propyl, iso-propyl (sample *a*), normal primary butyl, iso-butyl, tertiary butyl and amyl alcohols were used. Samples of technical quality of normal secondary butyl and diacetone alcohol were used. The former gave unstable emulsions with the Agral I solution, whereas good emulsions were given by iso-butyl and amyl alcohol. In other cases solutions were obtained at the alcohol concentrations used.

In view of the inertness of iso-propyl alcohol a sample of technical quality (sample *b*) was also used and, in order to investigate the possibility that impurities may confer fungicidal or phytocidal properties to the technical grade, a direct comparison was made between sprays prepared from the pure and the technical grades.

The inactivity of the mono-hydric alcohols as fungicides is surprising in view of the known physiological properties of these compounds. Their harmlessness to the foliage would indicate that they are suitable water-miscible solvents for use in sprays. Examples of their use for the preparation of suspensions of water-insoluble but alcohol-soluble compounds are given later in this communication, and trials of diacetone alcohol (which is free from excise restrictions) as a solvent for rotenone have been recorded elsewhere (2).

Two of the common glycols, or di-hydric alcohols, were examined, ethylene glycol and trimethylene glycol, both samples of technical quality. Both were completely miscible at the concentrations used. Spray trials, summarised in Table III, showed that these glycols closely resemble glycerol in their fungicidal and phytocidal properties. Glycerol, a tri-hydric alcohol, at 4 per cent. (11), proved to be not quite fungicidal but capable of causing slight injury to the leaves.

Table III.

No. of Exp.	Alcohol	Concentrate %	Adjuvant	Fungicidal properties	Action on leaf
83/31	Methyl	60	None	Usually N.F., occasionally N.Q.F.	No injury
141/31	,,	80	,,	N.Q.F.	,,
274/31	,,	90	,,	,,	,,
184/32	,,	90	,,	,,	,,
188/32	,,	100	,,	N.F.*	Slight "scorching" injury to tips and edges of 2 of the 4 leaves sprayed
116/31	Ethyl	60	,,	N.F.	No injury
129/31	,,	80	,,	,,	,,
130/31	,,	96	,,	N.F.†	Serious injury†
159/31	Propyl	50	0·25 % Agral I	N.F.	No injury
204/32	,,	70	0·15 % Agral I	N.F., with slight checking action at first	Severe "scorching" of tips of most leaves
131/31	Iso-propyl (*a*)	60	0·2 % Agral I	N.F.	Occasional slight injury to tip of leaf
186/31	,,	80	None	,,	No injury
261/31	,,	90	,,	,,	Serious injury to tip and edge of leaf
49/33	,,	50	0·25 % Agral I	,,	No injury
50/33	Iso-propyl (*b*)	50	,,	,,	,,
165/31	Butyl (primary)	50	,,	F.	Severe "scorching" injury to edge and tip of leaf
112/32	,,	20	,,	N.F., with slight checking action at first	No injury
141/32	,,	40	,,	N.Q.F. to N.F.	Marked injury to edge and tip of leaf
6/33	Butyl (secondary)	50	,,	N.Q.F.	No injury
91/33	,,	70	,,	N.F. ultimately, marked checking action	Slight injury to edge and tip of leaf
6/32	Iso-butyl	20	,,	N.F.	No injury
30/32	,,	40	,,	F., or nearly so	Slight injury to edge of leaf
140/32	,,	30	,,	N.F. ultimately, with checking action at first	No injury
177/31	Butyl (tertiary)	50	,,	N.F.	,,
187/32	,,	60	0·2 % Agral I	N.F., with some checking action	Occasional slight injury to tip of leaf
43/32	Amyl	16	0·25 % Agral I	F., or occasionally N.Q.F.	More or less serious injury in form of pale brown "burnt" areas
5/32	Diacetone	10	,,	N.F.	No injury
24/32	,,	40	,,	N.F., with checking action at first	Slight injury, usually at edge of leaf
77/31	Ethylene glycol	2	,,	N.F.	No injury
150/31	,,	8	,,	—	Serious injury, extending inwards from the edge
197/31	,,	6	,,	F., or very nearly so‡	No injury
23/32	,,	6	,,	F.	More or less serious injury to tip and edge of leaf
98/32	,,	4	,,	N.F.	Injury in form of blackish spots scattered over lamina
76/31	Trimethylene glycol	2	,,	,,	No injury
37/32	,,	6	,,	Apparently F., or nearly so	All the 6 leaves seriously injured at edge or tip
113/32	,,	4	,,	F., or N.Q.F.	Serious injury, chiefly at edge

* Except in Exp. 83/31, the hop plant was not the Hop "B18" but various other hop plants of seedling origin. The vigour of the mildew may have varied somewhat, accounting for the differences shown in, *e.g.* Exps. 184/32 and 188/32.

† Serious injury was caused here and there to the leaf tissue in the form of "burnt" brown areas, and in the browning and curling of the leaf edge—while the mildew patches were uninjured and reformed conidiophores.

‡ The hop plant used in Exp. 197/31 was not the Hop "B18" which was used in Exps. 23/32 and 98/32.

(b) *Phenols.*

Although the phenols cannot be described as industrial solvents, they are included at this stage because of their relationship to their hydrogenated derivatives, such as cyclohexanol, which are important and valuable solvents. Further, the phenols as a group are characterised by pronounced antiseptic and germicidal properties and a general physiological activity which might well extend to fungicidal properties. In the experiments with phenol (hydroxy-benzene) were included trials in which ethyl alcohol was added in order to determine to what extent the presence of the alcohol when used as a solvent for such materials as thymol and the naphthols would modify the fungicidal and phytocidal actions of the material tested. It will be seen from Table IV that the presence of alcohol has not altered the behaviour of phenol.

The sample of phenol used was of the commercial grade described as detached crystals. Cresol conforming to the B.P. 1914 and technical grades of cyclohexanol and methyl cyclohexanol were used. Thymol, 1-methyl-4-*iso*-propyl-3-hydroxy-benzene, was included on account of its known antiseptic properties and its relationship to cymene, a hydrocarbon used in trials recorded above. A saturated solution of thymol in 0·25 per cent. Agral I was found to contain approximately 0·1 per cent., and, because of this low solubility, the sprays at higher concentrations were prepared by the dilution of a 10 per cent. ethyl alcohol solution, by which means satisfactory suspensions were easily prepared. Good emulsions of cyclohexanol and methyl cyclohexanol were produced by agitation with 0·25 per cent. Agral I solutions, and these wetted normally in marked contrast to those containing an equal volume of cyclohexane or methyl cyclohexane.

The phenols examined all possess marked fungicidal properties, accompanied, especially in the case of thymol, by pronounced phytocidal activity. Cyclohexanol and methyl cyclohexanol, which provide a further example of the loss of phytocidal and fungicidal properties following hydrogenation, would appear to be safe spray solvents if their concentration in the final spray is not greater than 1–2 per cent. The discordant results obtained with cyclohexanol in Exps. 137/31, 259/31 and 11/32 were not subjected to further test as it was evident that cyclohexanol is insufficiently active to be used as a fungicide.

Naphthols. The naphthols, which are the mono-hydroxy-derivatives of naphthalene, possess marked bactericidal properties and β-naphthol has been recommended as a preservative of leather against mould

Table IV.

No. of Exp.	Material	Concentrate %	Adjuvant	Fungicidal properties	Action on leaf
156/30	Phenol	1	0·5% A	N.F.	No injury
29/31	,,	2	0·25% A	F., or N.Q.F.	Occasional slight injury to tip of leaf
89/31	,,	1·5	,,	N.Q.F.	No injury
136/31	,,	2·5	,,	,,	Slight or serious injury to edge of leaf
162/31	,,	2·0	10% E + 0·25% A	N.F.	Very slight injury to edge or tip of leaf
236/31	,,	2·0	,,	,,	No injury } The opposite leaves at the same nodes were used
235/31	,,	2·0	0·25% A	,,	No injury
30/31	Cresol	1·0	,,	F., or occasionally N.Q.F.	No injury
263/31	,,	1·5	,,	N.Q.F.	More or less serious injury to tip
86/31	,,	0·5	0·5% S	,,	No injury
160/31	,,	1·5	,,	N.F.	More or less serious injury
60/31	Thymol	0·1	0·25% A	N.F., some checking action at first	No injury
127/31	,,	1·0	10% E + 0·25% A	—	Lethal, the leaves were killed within 5 minutes
161/31	,,	0·5	5% E + 0·25% A	—	Lethal, the leaves were quickly killed
166/31	,,	0·25	2·5% E + 0·25% A	F.	Some injury*
75/32	,,	0·20	2% E + 0·25% A	,,	Serious injury†
172/32	,,	0·15	1·5% E + 0·25% A	N.F.	No injury
121/31	,,	0·1	1% E + 0·25% A	N.F., some checking action at first	,,
12/30	Cyclohexanol	2·0	0·5% A	N.F.	,,
70/30	,,	4·0	,,	,,	,,
43/31	,,	8·0	0·25% A	F., or just below fungicidal strength	,,
137/31	,,	10·0	,,	F., possibly S.F.‡	,,
259/31	,,	9·0	,,	N.F.	Slight "scorching" injury at edge or tip of leaf
11/32	,,	8·0	,,	F.	More or less serious injury at tip or edge of leaf
277/31	Methyl cyclohexanol	6·0	,,	N.Q.F.	No injury
28/32	,,	8·0	,,	F.	Serious injury, chiefly at edge
31/32	,,	7·0	,,	—	Lethal injury

A = Agral I. E = Ethyl alcohol. S = Soft soap (B.P.).

* The injury caused was in the form of numerous minute blackish spots (scattered over the lamina) which extended through to the lower surface.

† In the form of numerous minute "burnt" spots scattered over the lamina, often accompanied by injury to the edge of the leaf.

‡ The mycelial patches remained white.

Table V.

No. of Exp.	Naphthol	Concentrate %	Adjuvant	Fungicidal properties	Action on leaf	
124/31	α Sample (*a*)	0·5	10% E + 0·25% A	F.*	No injury	The opposite leaves at the same nodes were used
123/31	β Sample (*a*)	0·5	,,	F.†	No injury†	
185/31	α Sample (*a*)	0·25	5% E + 0·25% A	F.	No injury	
216/31	,,	0·25	,,	F., or just below fungicidal strength	No injury	The opposite leaves at the same nodes were used
217/31	β Sample (*a*)	0·25	,,	,, ,,	No injury	
39/32	α Sample (*b*)	0·25	5% D + 0·25% A	F.	Slight but distinct injury to edge of leaf	
115/32	,,	0·15	3% D + 0·25% A	,,	No injury	
25/32	,,	0·25	5% D + 0·25% A	F. (S.F.)	See ‡	The opposite leaves at the same nodes were used
26/32	α Sample (*c*)	0·25	,,	,,	See ‡	
40/32	β Sample (*b*)	0·25	,,	—	Serious injury	
87/32	,,	0·25	5% E + 0·25% A	F.	Occasional slight injury	
39/33	,,	0·2	4% D + 0·25% A	F. (S.F.)	No injury	The opposite leaves at the same nodes were used
40/33	β Sample (*c*)	0·2	4% D + 0·25% A	,,	No injury	
134/32	α Naphtholate	0·25	0·25% A	F.§	No injury	
193/32	,,	0·15	None	N.F., with slight checking action at first	,,	
145/32	β Naphtholate	0·25	,,	F.‖	No injury‖	

A = Agral I.   D = Diacetone alcohol.   E = Ethyl alcohol.

* The mildew patches were killed but not the underlying leaf tissue.

† The mildew patches were killed, together with the underlying leaf cells, extending through to the lower surface of the leaf, resulting in small dead isolated areas of leaf tissue. No injury was caused to the leaf elsewhere.

‡ Injury to the leaf tissue occurred in the form of numerous minute reddish brown transparent spots, about the size of pin-pricks, scattered over the lamina; no appreciable harm was caused to the leaf as a whole.

§ Exerted a disintegrating action on the mycelium, observable by the third day after spraying.

‖ The leaf cells underlying the mildew patches were killed, causing small dead areas extending to the lower surface of the leaf; no injury to the leaf tissue was caused elsewhere.

fungi (13). Three samples each of α- and β-naphthols were used, (*a*) and (*b*) being commercial grades and (*c*) of the pure A.R. grade. The sprays were prepared by the addition of an alcoholic solution of the naphthol to dilute Agral I solutions, a process which, at the concentrations used, gave perfect suspensions in which the particles, though crystalline, did not coagulate unless kept overnight. For the (*a*) samples, denatured ethyl alcohol and for the (*b*) samples, diacetone alcohol were used as the solvents. In other trials, the sprays were prepared by the addition of the theoretical quantity of sodium hydroxide necessary to form the naphtholates which are not only of ready solubility in water, but the solutions possess sufficient wetting properties to render the addition of a spreader unnecessary in obtaining a wetting of the mildew patches.

The spray trials, summarised in Table V, indicate that there is a sufficient margin of safety between the naphthol concentrations killing the fungus and those causing injury to the leaf to justify further trials of their fungicidal properties. The comparative trials made between commercial and pure samples of α- and β-naphthols suggest that commercial samples may be used for this purpose.

Of the dihydric phenols the samples used were from the ordinary laboratory supply and, of the trihydric phenols, two samples of pyrogallol, (*a*) heavy crystals and (*b*) resublimed, and one pure sample of phloroglucinol were used. The sprays were prepared by the solution of the required amount of the phenol in 0·25 per cent. Agral I.

From the results summarised in Table VI, it will be seen that these polyhydric phenols showed, with the exception of phloroglucinol, similar properties; all were fungicidal at concentrations when leaf injury became serious. The addition of ethyl alcohol as a solvent to the quinol spray had little effect upon its fungicidal and phytocidal actions.

Of the phenolic acids, salicyclic acid was selected as the monohydroxy-, protocatechuic acid as the dihydroxy- and gallic acid as the trihydroxy-derivative. To complete the series, benzoic and tannic acids were included.

Protocatechuic acid is of interest as Angel, Walker and Link (1) isolated this acid from pigmented onion scales resistant to onion smudge and established, by *in vitro* tests, its high toxicity to *Colletotrichum circinnans*, the causal organism of this disease.

The naturally occurring derivatives of polyhydroxy-benzoic acids which are grouped under the name tannic acid have also been employed as spray materials, *e.g.* for the preparation of nicotine tannate (7), which has been found a promising stomach insecticide. Further, Cook and Taubenhaus (4) reported that tannin, at concentrations of 0·1–0·6 per cent., retarded the *in vitro* growth of certain parasitic fungi, whilst Johnstone (8) found it toxic to spores of apple scab (*Venturia inaequalis*).

In the case of compounds insufficiently soluble in dilute Agral I solution, the sprays were prepared by the addition of the requisite amount of a 10 per cent. solution of the compound in 96 per cent. ethyl alcohol to the Agral I solution.

The phenolic acids examined, as shown in Table VI, exhibited pronounced phytocidal properties which show a tendency to be reduced as the number of hydroxyl groups increase. Tannic acid would appear a safe spray ingredient.

The polyphenolic derivatives are of special interest in that certain of them have been employed by Tattersfield (14) as constituents of pyrethrum dusts when they serve as anti-oxidants to prevent loss of toxicity by oxidation. Of the compounds which Tattersfield found effective as protectants tannic acid would appear, on the basis of the experiments on hop leaves described above, to be the safest as regards foliage injury. It is of interest to note that phloroglucinol, which Tattersfield found ineffective as an anti-oxidant, was deficient in fungicidal and phytocidal properties.

Saligenin, salicylaldehyde and vanillin were included as representative phenolic alcohols and aldehydes. At 1 per cent. salicylaldehyde gave an unstable emulsion when shaken with dilute Agral I solution. These materials proved inactive and it is of interest to note that the phenolic esters, anisole and guaiacol, were less active than phenol and catechol, a reduction which may be associated with the substitution of the methoxy- for the hydroxy-group in these compounds.

In view of the results obtained by Morris (12) which showed *p*-nitrophenol to be a useful fungicide for the protection of textile materials from mould attack, tests were made with this compound and with picric acid. As was expected in view of the observations by Tattersfield, Gimingham and Morris (15), on the extreme injury to foliage of dinitro-*o*-cresol and its salts, the phytocidal properties of the two nitro derivatives tested were too great to permit of their use as fungicides for application to foliage.

Further work in the search for antiseptics for use in protecting textile materials from "mould" fungi, carried out by Fargher, Galloway and Probert (6), at the Shirley Institute, lead to the discovery of marked fungicidal properties in salicylanilide. We have been able, through the courtesy of Imperial Chemical Industries, Ltd., to carry out tests not only with various preparations marketed under the name "Shirlan" containing this derivative of salicylic acid, but with salicylanilide and its sodium salt "Shirlan W.S."

Table VI.

No. of Exp.	Material	Concentrate %	Adjuvant	Fungicidal properties	Action on leaf
14/31	Catechol	1	0·25% A	—	Lethal
70/31	,,	0·25	,,	N.F.	No injury
134/31	,,	0·5	,,	—	Severe injury, killing or nearly killing leaf
192/31	,,	0·4	,,	F.*, rarely N.Q.F.	No injury
258/31	,,	0·3	,,	N.Q.F.	Occasional slight injury
8/31	Resorcinol	1	,,	—	Lethal
69/31	,,	0·25	,,	N.F.	Occasional slight injury
26/31	Quinol	1	,,	F., or very rarely just below fungicidal strength	Occasional slight injury, usually at edge
37/31	,,	0·5	,,	F., or just below fungicidal strength	No injury
41/32	,,	1	,,	F., or very rarely just below fungicidal strength	More or less serious injury occasionally caused
250/31	,,	1	,,	F., or just below fungicidal strength	Occasional slight injury } The opposite leaves at the same nodes were used
251/31	,,	1	10% E + 0·25% A	,, ,,	Occasional slight injury }
21/31	Pyrogallol (*a*)	1	0·25% A	—	Serious, almost lethal, injury
36/31	,,	0·5	,,	Uncertain†	Slight injury to edge
135/31	Pyrogallol (*b*)	0·5	,,	N.F.	Slight but distinct injury to lamina
27/31	Phloroglucinol	1	,,	,,	No injury
125/31	Benzoic acid	1	10% E + 0·25% A	F., or just below fungicidal strength	,,
179/31	,,	1·5	15% E + 0·25% A	—	Serious injury
35/31	Salicylic acid	0·15	0·25% A	N.F., with some checking action at first	No injury
126/31	,,	1	10% E + 0·25% A	F.‡	Distinct injury to edge of 2 of the 5 leaves sprayed
187/31	,,	0·5	5% E + 0·25% A	—	Serious injury
278/31	,,	0·3	3% E + 0·25% A	N.Q.F.§	See §
120/31	Potassium salicylate	1	0·25% A	N.F.	Serious injury
24/31	Protocatechuic acid	1	,,	,,	No injury

25/31	Gallic acid	1	0·25 % A	Just below fungicidal strength	No injury
75/31	,,	0·5	,,	N.F.	,,
140/31	,,	1·5	,,	N.Q.F.	Occasional slight injury to tip of leaf
58/31	Tannic acid	1	,,	N.F.	No injury
149/31	,,	2	,,	,,	,,
196/31	,,	4	,,	,,	,,
279/31	,,	8	,,	,,	,,
49/31	Saligenin	1	,,	,,	,,
68/31	Salicylaldehyde	1	,,	,,	,,
48/31	Vanillin	0·86	,,	,,	,,
28/31	Anisole	1	,,	,,	,,
59/31	Guaiacol	1	,,	N.F., with definite action[‖]	,,
47/31	*p*-nitro-phenol	1	,,	N.F.	,,
85/31	,,	0·25	,,	—	Lethal
38/31	Picric acid	0·5	,,	N.Q.F.	Serious injury
142/31	,,	0·75	,,	N.Q.F.[¶]	No injury
				F., or rarely just below fungicidal strength	Slight or serious injury
143/31	Sodium picrate	0·75	0·5 % S	N.F.	No injury

A = Agral I. E = Ethyl alcohol. S = Soft soap (B.P.).

[*] The mycelial patches were darkened when killed.

[†] Unequal action was shown, some of the mildew patches being killed, while others survived and produced conidiophores within 5 days.

[‡] The mildew patches were blackened, together with the underlying leaf-cells.

[§] The leaf-tissue underlying the mildew patches was killed, extending to the under-surface, so that conspicuous dead areas were produced over the lamina; the mildew patches were, however, not entirely killed, and conidiophores were produced at their margins by the twelfth day.

[‖] The mycelium of the patches was partly disintegrated; fresh conidiophores were produced at the edge of the patch by the sixth day and the solution was ultimately non-fungicidal.

[¶] Much of the mycelium was stained yellow and killed, but the solution was not quite fungicidal, scattered conidiophores re-forming at the margins of many patches.

Table VII.

No. of Exp.	Material	Salicylanilide concentrate %	Adjuvant	Fungicidal action	Action on lea
13/31	Shirlan W.S.	1	0·25% A	F. (S.F.)*	No injury
73/31	,,	0·5	,,	,,	,,
101/31	,,	0·5	0·5% S	,,	,,
144/31	,,	0·25	0·25% A	Just below fungicidal strength	,,
72/31	Shirlan Paste (*a*)	1	,,	N.F.	,,
191/31	,,	1	,,	N.Q.F. to N.F.	,,
234/31	Shirlan	1	15% E + 0·25% A	Just below fungicidal strength	,,
281/31	,,	1	15% E + 0·5% S	F.	,,
190/31	Shirlan Paste (*b*)	1	0·5% S	Apparently F.	,,
248/31	,,	1	0·25% A	N.F., or rarely N.Q.F.†	,,
249/31	,,	1	0·5% S	F., or just below fungicidal strength†	,,
78/33	Shirlan A.G.	0·5	None	N.F.	,,
79/33	"D.S. 226"	0·5	,,	,,	,,

A = Agral I. E = Ethyl alcohol. S = Soft soap (B.P.).

* By the second day the mycelium was floccoso-collapsed and dead; the dead patches of mildew remain conspicuously white.

† The 8 leaves sprayed in Exps. 248, 249 were opposite leaves at the same nodes. It was clear that the suspension, with soft soap, had increased fungicidal powers.

Shirlan Paste has been found by Bewley and Orchard (3) to be effective when applied with Agral I in the control of tomato-leaf mould, *Cladosporium fulvum*, and, in preliminary work, active against the powdery mildews of cucumber, *Erysiphe cichoracearum*, of chrysanthemum, *Oidium Chrysanthemi*, and of rose, *Sphaerotheca pannosa*.

Trials with the salicylanilide preparations are recorded in Table VII, from which it will be seen that the sodium salt is highly effective. It was considered possible that the failure of "Shirlan Paste" may have been due to low solubility or to an interfering action by the protective colloid present. Further trials were accordingly made of suspensions prepared by the addition of an alcoholic solution of salicylanilide to dilute Agral I solutions, of the effect of the use of an alkaline spreader, *e.g.* soft soap, instead of Agral I, and finally of other Shirlan suspensions submitted for examination. The results suggest that the Shirlan preparations are effective in a single application in killing the hop powdery mildew only under conditions when a high proportion of the salicylanilide is in solution.

(3) ESTERS.

In describing the trials made of esters selected from the wide range now commercially available as solvents and plasticisers, it is convenient to classify them according to the carboxylic components. Attention was first given to fatty acid esters which are of special interest because of the high fungicidal properties of glyceride oils which are the glyceryl esters of higher fatty acids.

The samples used were either from ordinary laboratory stock or were of technical grades of the following specifications:

Cyclohexanyl acetate:	Boiling range 170–176° C. Sp.gr. 0·947. Ester content 80–90 per cent. (remainder cyclohexanol).
Methyl cyclohexanyl acetate:	Ester content 80–90 per cent.
Dimethyl cyclohexanyl oxalate:	Ester content 95–100 per cent.
Ethyl lactate:	Boiling range 145–160° C. Sp.gr. 1·03. Ester content 99–100 per cent. Neutral to litmus.
Ethyl tartrate:	Ester content 99–100 per cent.
Diethyl phthalate:	Ester content 99–100 per cent.

Table VIII.

No. of Exp.	Ester	Concentrate %	Adjuvant	Physical state	Fungicidal action	Action on leaf
91/32	Amyl acetate	1	0·25% A	Stable	N.F.	Slight injury to tip of 1 of the 6 leaves sprayed
160/32	,,	4	,,	,,	F., or rarely just below fungicidal strength	Definite injury to edge
89/32	Ethylene glycol diacetate	1	,,	In solution	N.F.	No injury
120/32	,,	4	,,	,,	,,	,,
178/32	,,	6	,,	,,	,,	Severe injury
26/32	Cyclohexanyl acetate	1	,,	Stable	Apparently just below fungicidal strength	More or less serious injury, usually at tip
117/32	Methyl cyclohexanyl acetate	1	,,	,,	F.	Slight injury to tip or edge
83/32	Diacetin	2	,,	In solution	N.F.	Serious, or even fatal, injury
118/32	,,	1	,,	,,	,,	More or less serious injury in form of "burnt" spots
73/32	Triacetin	1	,,	,,	,,	Serious injury
85/32	Ethyl butyrate	1	,,	Stable	,,	No injury
119/32	,,	4	,,	,,	F., or just below fungicidal strength	,,
162/32	Isobutyl butyrate	0·5	,,	Unstable	N.F.	,,
174/32	,,	1·5	,,	,,	Below fungicidal strength	Occasional slight "scorching" injury
18/33	,,	2·0	,,	,,	F. (S.F.)	Slight injury to edge and tip
48/32	Ethyl oleate	1	,,	,,	F.*	Serious injury to edge and tip
108/32	,,	0·5	,,	,,	F.†	More or less serious injury to edge and tip
135/32	,,	0·25	,,	,,	N.Q.F.	No injury
144/32	,,	0·25	0·13% O	Stable	Below fungicidal strength	,,
194/32	,,	0·5	,,	,,	N.F., with distinct checking action at first	,,
62/33	,,	0·4	0·25% A	Unstable	F. or S.F.	,,
63/33	,,	0·4	0·13% O	Stable	N.Q.F.‡	,,
205/32	Methyl cyclohexanyl stearate	0·5	0·25% A	Unstable	F., possibly S.F.§	,,

25/32	Dimethyl cyclohexanyl oxalate	1	0·25 % A	Unstable	—	Lethal
71/32	,,	0·5	,,	,,	F.[‖]	Serious injury, in form of brown areas of dead leaf cells
102/32	,,	0·25	,,	,,	F., or perhaps occasionally just below fungicidal strength	Slight injury, in form of brown areas of dead leaf cells
157/32	,,	0·25	0·13 % O	Stable?	Just below fungicidal strength	Slight or severe injury, in form of brown areas of dead leaf cells
64/33	,,	0·25	0·25 % A	Unstable	From fungicidal to well below fungicidal strength	No injury
65/33	,,	0·25	0·13 % O	Stable?	From fungicidal to well below fungicidal strength	Serious "scorching" at edge of 1 of the 7 leaves sprayed
7/32	Ethyl lactate	4	0·25 % A	In solution	N.F.	No injury
14/33	Amyl lactate	1	,,	Stable	,,	,,
56/33	,,	4	,,	,,	F.	,,
68/33	Ethyl tartrate	2	,,	In solution	N.F.	Injury in form of dead areas of leaf cells of varying size
11/33	Amyl tartrate	1	,,	Unstable	—	Lethal
161/32	Ethyl benzoate	0·5	,,	Stable	Below fungicidal strength	No injury
55/33	,,	1	,,	,,	F. (S.F.)	Injury in form of minute brown "scorched" areas
10/33	Diethyl phthalate	1	,,	,,	—	Lethal
36/33	,,	0·25	,,	,,	Apparently F.	Serious "scorching" injury
88/33	,,	0·125	,,	,,	Below fungicidal strength	No injury
3/33	Dibutyl phthalate	1	,,	Unstable	—	Serious, or fatal, injury
13/33	,,	0·5	,,	,,	—	Lethal

A = Agral I. O = Sodium oleate. Stable = Stable emulsion wetting normally. Unstable = Unstable emulsion giving "oily" wetting.

* Very pronounced action; the mycelium of the patches was disintegrated and more or less completely removed, leaving discoloured (blackish-brown) areas of leaf cells where the patches had been.

† The dead mycelium remained chalk-white, with the underlying leaf cells darkened.

‡ The opposite leaves, at the same nodes, of the 7 leaves sprayed in Exp. 62/33 were used. In Exp. 62 the emulsion was F. or S.F., all the patches being killed and turned blackish brown; in Exp. 63 the emulsion was not so fungicidal; some of the patches were killed while others survived to produce a few scattered conidiophores—and the darkening of the patches was not so pronounced.

§ Rarely, conidiophores massed in the furrows of the leaf were not wetted and killed.

‖ The mycelial patches were completely removed, leaving small brown insunken patches of dead leaf cells where they had been.

The results of spray trials, summarised in Table VIII, showed that all the esters examined had pronounced fungicidal and phytocidal properties, which appear to be influenced by solubility factors. Thus ethylene glycol diacetate, ethyl lactate and ethyl tartrate, were non-fungicidal at 2 and 4 per cent. and miscible with the Agral I solution at these concentrations. With diacetin and triacetin, also miscible, phytocidal properties appeared at 1 per cent., properties which are shared by tributyrin ((11), p. 236). Tributyrin proved to be fungicidal at 0·5 per cent., but caused slight injury to the leaf which was serious at 1 per cent. With the insoluble esters high fungicidal properties were associated with foliage-injuring character, which would prevent their practical use as fungicides. As a general rule it was found that this physiological activity was more pronounced with those esters giving unstable emulsions. As with the glyceride oils and cymene, the more stable emulsions given by agitation with dilute sodium oleate solutions were less active than the unstable Agral I emulsion in the case of ethyl oleate. Dimethyl cyclohexanyl oxalate, however, did not follow this rule.

SUMMARY.

The fungicidal and phytocidal properties of manufactured hydrocarbons and their simpler hydroxyl-derivatives and esters have been examined by application in spray-form to young leaves of hops bearing powdery patches of the hop powdery mildew (*Sphaerotheca humuli* (D.C.) Burr.). The sprays were prepared by agitation with 0·25 per cent. Agral I solutions. For ease of description the term fungicidal is applied only to sprays which are lethal to the fungus, whilst a spray is termed phytocidal when injury to the leaf results at areas not invaded by the fungus.

1. Benzene was fungicidal and phytocidal at concentrations of 2 per cent., whereas the hydrogenation products, cyclohexane, methyl cyclohexane and dekalin, were inactive at this concentration. Fungicidal and phytocidal properties were shown at 7 per cent. of the two former, and 3–4 per cent. of the latter.

2. Cymene and the terpenes, carvene, phellandrene, dipentene, were fungicidal and phytocidal at 0·5–1 per cent. The samples of turpentine and pine oil examined showed properties similar to those of the above terpenes. Geraniol proved to be fungicidal and phytocidal at 0·4 per cent. whereas with eucalyptus oil and fenchone concentrations of 2 per cent. and 1 per cent. respectively were required before these properties were shown.

3. The lower aliphatic alcohols proved inert though fungicidal and

phytocidal properties increased with molecular weight. Iso-propyl and diacetone alcohol (a technical grade) exhibited phytocidal properties at 90 per cent. and 40 per cent. respectively. A technical grade of iso-propyl alcohol had no action at 50 per cent. The glycols examined proved phytocidal at concentrations of the order of 4 per cent.

4. Of the phenols, hydroxybenzene caused injury at 2 per cent., cresol at 1·5 per cent. and thymol at 0·2 per cent. α- and β-naphthol were fungicidal at 0·15 and 0·20 per cent. and, except in one experiment, caused no leaf injury at concentrations below 0·5 per cent. As results similar to these were obtained with commercial grades, α- and β-naphthols would appear to be worth further trial as fungicides for the control of powdery mildews. The hydrogenated products cyclohexanol and methyl cyclohexanol did not exhibit fungicidal or phytocidal properties until the concentration reached 8–10 per cent.

5. The polyhydric phenols, catechol, resorcinol, quinol and pyrogallol, were fungicidal and phytocidal at concentrations of the order of 1 per cent. Phloroglucinol and the phenolic esters, anisole and guaiacol, were non-fungicidal and non-injurious to the leaf at this concentration.

6. The phenolic acids exhibited fungicidal properties at concentrations when leaf injury became serious; thus benzoic acid at 1–1·5 per cent., salicylic acid at 0·5 per cent., gallic acid at 1·5 per cent., protocatechuic acid at 1 per cent. and tannic acid at 8 per cent. were inactive.

7. Of the miscellaneous phenolic derivatives examined, saligenin, salicylaldehyde and vanillin were inactive at concentrations of about 1 per cent. whereas the nitro derivatives, para-nitro-phenol and picric acid, proved strongly phytocidal.

8. Salicylanilide, when applied in the form of its sodium salt, proved fungicidal at 0·5 per cent. and almost fungicidal at 0·25 per cent., and did not cause injury to the leaf at 1 per cent. Suspensions containing 1 per cent. salicylanilide, however, proved non-fungicidal though showing more activity when soap was used as the spreader. The results suggest that solubility factors may influence the fungicidal behaviour of salicylanilide.

9. The esters examined exhibited, as a class, high fungicidal and phytocidal activity, in which solubility factors appeared to play an important part. Thus the water-soluble esters, ethylene glycol diacetate and ethyl lactate were non-fungicidal and non-injurious at 4 per cent., whereas the insoluble esters, ethyl oleate, dimethyl cyclohexanyl oxalate and diethyl phthalate, were fungicidal and phytocidal at 0·5 per cent. Di- and triacetin, however, showed phytocidal properties at 1 per cent.

in spite of their soluble character. The other esters examined, amyl acetate (4 per cent.); cyclohexanyl acetate (1 per cent.); methyl cyclohexanyl acetate (1 per cent.); ethyl butyrate (4 per cent.); iso-butyl butyrate (1·5 per cent.); amyl lactate (4 per cent.); ethyl tartrate (2 per cent.); amyl tartrate (1 per cent.); ethyl benzoate (1 per cent.) and dibutyl phthalate, showed fungicidal and/or phytocidal properties at the concentrations quoted in brackets after each. None proved likely to be of practical value as fungicides.

10. In the case of cymene, carvene and ethyl oleate, but not with dimethyl cyclohexanyl oxalate, it was found that sprays prepared with 0·13 per cent. sodium oleate as the emulsifier were less active fungicidally and phytocidally than sprays of similar oil concentration emulsified with Agral I.

It is suggested that these differences are associated with the amount of oil retained on the leaf after spraying, which in turn may be influenced by the stability of the emulsion.

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STUDIES ON CALCIUM CYANAMIDE.

IV. THE USE OF CALCIUM CYANAMIDE AND OTHER FORMS OF NITROGEN ON GRASSLAND.

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AMONG the numerous investigations of nitrogenous fertilisers on grassland that have been reported in recent years, little attention has been given to differences in the action of widely different forms of nitrogen. Such differences might be expected to appear especially clearly with this crop, which remains in the ground throughout the year and completely occupies the soil with its roots. It has the additional advantage that repeated cutting is possible, giving samples over a lengthened growing period, and enabling a closer examination of the action of the nitrogen to be made.

Experiments with calcium cyanamide (the commercial form of calcium cyanamide, $CaCN_2$) were therefore made on pasture grassland, in order to examine its reputation for being "slow acting" in comparison with sulphate of ammonia. As it was possible that this slow action would allow the fertiliser to be applied in late autumn in order to secure an "early bite" in the spring, autumn and winter applications were especially studied. In the first experiment several forms of nitrogen applied in winter were compared with a spring dressing of sulphate of ammonia. This experiment was repeated in the following year, and in addition a direct comparison of calcium cyanamide and sulphate of ammonia was made in both autumn and spring.

In the experiments with winter nitrogen, two of the treatments contained some of their nitrogen as dicyanodiamide. This compound ($NH_2.C(:NH).NH.CN$) is known to check nitrification in the laboratory, at concentrations which are not appreciably toxic to plants. It is formed when superphosphate is mixed with calcium cyanamide, to an extent which may be controlled by varying the conditions of mixing (cf. Richardson (1)). The substance therefore seemed a useful one to employ with the idea of reducing any loss of nitrogen due to nitrification followed by winter leaching. The dicyanodiamide used was prepared by boiling calcium cyanamide with water, crystallising out and recrystallising. Its melting-point was 200–202° C. The writer is indebted to Dr E. H. Farmer for permission to use the Whiffen Laboratory at the Imperial College of Science and Technology for its preparation.

As in the earlier cyanamide investigations (2) soil analyses were made in addition to the studies of the plant. Nothing was known when the work was begun about the behaviour of added ammonia in grassland soils, and in this respect the results are not without general interest.

THE INORGANIC NITROGEN OF GRASSLAND SOILS.

(*Stackyard Field experiment*, 1929–30.)

Young grassland was chosen for this experiment; the soil, the heavy loam with flints of Rothamsted, having been sown with a seeds mixture in the spring of 1928 (for further details of management see later under "Herbage").

In comparison with the old grassland soil of the Rothamsted Park, the soil had more flints near the surface, and was stickier to handle but held less water in the winter. It nitrified more vigorously, *i.e.* it produced more nitrate and less ammonia on incubation. The soil was naturally well drained, and it had been chalked while under cultivation; its reaction was now *p*H 6·5. There was no "mat," and roots were numerous to the depth of sampling (8 in.).

The treatments compared were:

(1) No nitrogen.
(2) Winter sulphate of ammonia (0·4 cwt. nitrogen per acre).
(3) Winter sulphate of ammonia (0·2 cwt. nitrogen) with dicyanodiamide (0·2 cwt. nitrogen).
(4) Winter calcium cyanamide (0·4 cwt. nitrogen).
(5) Winter calcium cyanamide (0·2 cwt. nitrogen) with dicyanodiamide (0·2 cwt. nitrogen).
(6) Spring sulphate of ammonia (0·4 cwt. nitrogen).

The 0·4 cwt. per acre of nitrogen applied corresponds to 2 cwt. per acre of sulphate of ammonia or calcium cyanamide. This represents approximately 20 mg. of nitrogen per kg. of dry soil in the samples taken. There was sixfold replication of treatments, giving thirty-six plots which were sampled and analysed separately in two blocks on consecutive days.

In sampling the soil a semi-cylindrical tool of narrow bore was used, to reduce the disturbance of the soil through repeated samplings. The depth of 8 in. was decided on after considering the results of an experiment with fallow during the previous winter (Crowther and Richardson (2)); it was approximately the depth of the old ploughed layer.

The general procedure was to take a dozen or more cores per plot, the sample from each plot (amounting to 150–200 gm.) being collected in a separate bottle. In the laboratory the soil was broken into fine crumbs, larger flint or vegetable fragments and roots being removed, and 100 gm. were taken for the preparation of an extract by the modified Carsten-Olsen method (Crowther and Richardson, *loc. cit.*). The extracts, containing toluene as a preservative, were always prepared on the day of sampling, the ammonia and nitrate distillations being carried out during subsequent days.

At first a separate 50 gm. subsample was taken from each plot sample for dry matter determination, but the standard error of the dry-matter values (0·43 per cent. of the weight of the samples, for a single plot) proved to be much lower than that of the mineral nitrogen. Subsequently, therefore, four to six composite samples were made and the dry matter was determined in these.

The complete sampling of the thirty-six plots was continued, usually at fortnightly intervals, until there was no further significant difference between treatments (mid-April). This gave the data from which the mean values and standard errors in Table I were calculated. Subsequently, sets of two or three treatments were sampled by plots, but there were no more differences between treatments that could be called significant in terms of the variance of the last complete sampling. The results of these samplings are not given here; they appeared in Fig. 8 of the previous paper (Crowther and Richardson (2)).

As a concise summary of the meteorological conditions during the experiment, Table I contains the mean soil temperature in degrees Fahrenheit at 4 in. and the total amount of drainage in inches in the 20 in. drain gauge with bare soil. Both of these sets of data are for the interval since the previous sampling (except the first one, which is taken from the time of applying the fertilisers).

The results showed, as might have been expected, that the variation between individual values of a treatment was greater where nitrogen had recently been added than on the untreated plots or those treated some time earlier. This was particularly noticeable in the ammonia values, where a simple test confirmed that the variance was higher with high treatment means than with low ones.

Table I. *Soil inorganic nitrogen, Stackyard Field.*

Winter dressings, December 6th, 1929; spring dressing, February 17th, 1930.

Treatment	Dec. 18, 1929	Dec. 31, 1929	Jan. 14, 1930	Jan. 28, 1930	Feb. 18, 1930	Mar. 4, 1930	Mar. 18, 1930	Apr. 1, 1930	Apr. 15, 1930
Ammonia N in mg./kg. dry soil (mean of six plots).									
1. No N	5·0	1·9	2·5	2·1	2·6	2·6	2·1	2·1	2·2
2. W. S/A	18·8	5·6	5·4	3·6	3·4	2·9	2·2	2·4	2·0
3. W. S/A + dicy.	11·6	5·5	6·0	3·0	2·9	3·8	2·2	2·3	2·2
4. W. Cy.	14·2	4·0	5·0	2·8	2·7	3·0	2·3	2·3	2·3
5. W. Cy. + dicy.	7·4	3·1	4·9	3·2	3·2	3·5	2·2	2·3	2·2
6. S. S/A	4·4	2·0	2·9	2·3	17·9	10·6	5·5	2·9	2·3
S.E. (on logarithmic basis) as % of treatment mean	5·7	13·5	9·5	10·7	3·8	8·6	10·4	8·9	5·6
Nitrate N.									
1. No N	1·5	1·4	1·3	1·0	1·1	1·2	0·7	1·8	0·9
2. W. S/A	3·6	2·0	1·9	1·9	1·7	1·6	0·7	1·4	0·8
3. W. S/A + dicy.	2·8	1·9	1·8	1·4	1·2	2·2	1·1	1·8	0·8
4. W. Cy.	4·2	2·4	2·5	1·9	1·4	1·7	0·8	1·5	0·9
5. W. Cy. + dicy.	3·2	2·1	1·9	1·6	1·6	1·4	0·6	1·8	1·0
6. S. S/A	2·0	1·1	1·2	0·8	1·2	2·5	1·6	1·9	0·8
S.E. (mg./kg.)	0·39	0·21	0·17	0·16	0·16	0·21	0·18	0·16	0·10
As % of treatment mean	13·7	11·6	9·7	10·7	11·6	11·8	19·6	9·6	11·5
Soil-dry matter as per cent. of fresh soil.									
General mean	78·2	79·0	78·9	78·9	79·0	79·9	79·1	81·6	79·8
Soil temperature and drainage.									
Mean temp. at 4 in. in ° F.	40·9	36·6	38·7	40·1	36·1	35·5	38·5	40·3	44·1
Drainage in inches	1·98	2·28	2·10	0·77	0·97	0·00	0·70	0·01	0·24

To allow for this, the standard errors of the ammonia values were calculated on the logarithms of the actual determinations. The values so obtained were considerably more uniform over the whole period of sampling than were the simple standard errors. For nitrates, where the range of values was much less than for ammonia, simple standard errors were calculated.

The general course of the soil ammonia and nitrate levels may be appreciated from Fig. 8 in the previous paper (Crowther and Richardson (2)). It may be added that in preparing this figure the diluting effect of soil moisture on the Carsten-Olsen extracts was overlooked, so that the values shown were too low by 8–10 per cent. This does not affect the *relative* positions of the curves. As the presentation there took no account of the treatments receiving dicyanodiamide, nor of the standard errors of the determinations, a more detailed consideration of the results follows.

The rapid disappearance of all forms of added nitrogen in both winter and early spring is noteworthy (compare Table II). The soil temperature was, if anything, lower after the early spring than after the winter application; the initial rate of disappearance was possibly a little slower in the early spring, but in both seasons the nitrogen added as sulphate of ammonia was removed so rapidly that three-fourths had gone in 3–4 weeks. Subsequent work (Richardson(3)) has shown that later in the spring the rate of disappearance increases, so that only a few days may then be required for the removal of three-fourths of the nitrogen from a heavy dressing of sulphate of ammonia. What proportion of this nitrogen is secured by the plant is a question that will be considered later in connection with the recovery of the nitrogen in the herbage.

Table II. *Disappearance of soil inorganic (ammonia and nitrate) nitrogen.*

Differences from untreated soil, as per cent. of nitrogen added.
Winter dressings applied December 6th; spring dressing February 17th.

	Dec. 18	Dec. 31	Jan. 14	Jan. 28	Feb. 18	Mar. 4	Mar. 18	Apr. 1	Apr. 15
W. S/A	80	22	18	12	7	4	0	0	-1
W. S/A + dicy.	40	20	20	6	2	10	2	1	0
W. Cy.	60	16	18	8	2	4	1	0	0
W. Cy. + dicy.	20	10	15	8	6	6	0	1	0
S. S/A	—	—	—	—	77	46	22	4	0

The differences between treatments may best be examined for the separate ammonia and nitrate determinations, comment being restricted to statistically significant differences. With *winter sulphate of ammonia*, although the soil ammonia fell off rapidly at first, it remained above that of the untreated soil for some 10 weeks. Nitrate did not accumulate to the extent of more than 1 or 2 mg./kg., but it remained above the untreated soil for the same period. With *spring sulphate of ammonia*, although the initial rate of disappearance of the added nitrogen was about the same as in winter, disappearance was more rapid when the soil warmed up in April, so that the soil ammonia remained above the untreated for only 6 weeks. The added inorganic nitrogen was completely removed from the soil by mid-April. Nitrate accumulated even less than in the winter and disappeared still more rapidly, a significant difference from the untreated soil lasting for only 4 weeks. As there was little drainage for some time after the sulphate of ammonia was applied, the low nitrate level cannot be attributed to leaching.

Although the soil ammonia from *winter calcium cyanamide* was frequently below that from sulphate of ammonia the difference was significant on only two occasions—on the first sampling, 10 days after application, and again in mid-February. Soil nitrate, rather unexpectedly, showed the opposite tendency, being for the first 6 weeks slightly higher with calcium cyanamide, although the difference was only once significant. This might be attributed to a reduction in nitrate uptake by the herbage following a slight check to the herbage from the cyanamide.

The ammonia from calcium cyanamide was completely removed from the soil before that from sulphate of ammonia, for the difference from the untreated soil had fallen below significance 7 weeks after application. Nitrate nitrogen persisted a little longer, but it had gone by the tenth week.

It is thus clear that, so far as soil inorganic nitrogen is concerned, the winter application of calcium cyanamide did not give a more prolonged supply of nitrogen than did sulphate of ammonia.

If calcium cyanamide had appreciably checked nitrification a higher ammonia level might have been expected from cyanamide than from sulphate of ammonia after the first few days. This was observed in uncropped soils in pots (2). Its absence here cannot, however, be taken as evidence that there was no delay in nitrification, for the extra ammonia may have been removed directly by the herbage (4).

In examining the behaviour of soils which received *dicyanodiamide*, it must be remembered that only half of the added nitrogen was present as sulphate of ammonia or calcium cyanamide. This was reflected in the soil ammonia values 10 days after application, when both treatments receiving dicyanodiamide were below those without dicyanodiamide. Subsequently, however, there were no significant differences (except once, with sulphate of ammonia in mid-February). Greater precision in examining the action of dicyanodiamide was obtained by comparing the twelve plots receiving half their nitrogen in this form with the twelve receiving all their nitrogen as sulphate of ammonia or calcium cyanamide. This confirmed the observation that there were no significant differences in soil ammonia after the first sampling; soil nitrate values were significantly lower in the presence of dicyanodiamide in three out of the first four samplings, but not subsequently. Soil nitrates were higher in the treatments receiving dicyanodiamide than in the untreated soil, in the first four samplings. Dicyanodiamide therefore retarded, but did not completely inhibit nitrification in this experiment. There was no evidence in the later measurements that dicyanodiamide nitrogen added in the winter became available in the spring.

THE GROWTH AND YIELD OF HERBAGE.

(a) *Stackyard Field experiment*, 1929–30.

The soil of this experiment has already been described, while its agricultural history appears at the head of Table III. The area chosen for the experiment was almost level; it was prepared by removing flints and dung, rolling, and mowing with a special lawn mower set to cut high and fitted with a basket (designed by R. G. Warren) to catch the herbage as completely as possible. The fertilisers were diluted with sand to uniform bulk and sprinkled on by hand from a vessel with a perforated end. The six randomised blocks of the experiment were grouped in two major blocks to give a compact lay-out.

The procedure of sampling the herbage varied at first, but in the later cuts the whole produce of each plot was weighed as soon as cut; it was then mixed and small handfuls were taken at random to make up a sample of 1 lb., which was kept in a relatively large, porous bag to avoid overheating. These samples were transferred to a warm room at intervals during the day, and, after being spread and partly dried there, were finally dried for 2 days in a steam-oven. After weighing for dry matter the samples were either ground separately, or bulked and then subsampled and ground for nitrogen determinations.

Herbage. The effect of the winter applications was slow in appearing, but by the end of January some of the no-nitrogen plots could be distinguished by their paler appearance. When spring sulphate of ammonia was applied, in mid-February, the plots with winter nitrogen were all greener than the remainder. The effect of the spring nitrogen was visible after about a month (the average temperature being low in the interval), and it was well developed by the beginning of April. By this time only a trace of the spring nitrogen remained in the soil in the inorganic form.

When the first cut was made, at the end of April, spring sulphate of ammonia had given a strikingly heavier and greener growth of grass than the winter treatments, while the no-nitrogen and some of the dicyanodiamide plots looked relatively thin and pale. Subsequent cuts were not made at regular intervals, but whenever the grass had reached a height—from 3 to 5 in.—suitable for grazing by stock under the "intensive" system.

The differences in growth with treatment were less marked with the second cut in the middle of May than they had been with the first. By the end of May, when clover was developing vigorously, it was evident

Table III. *Stackyard Field, yield and nitrogen content of herbage*, 1930.

Previous cropping. Seeds mixture sown under winter oats in April 1928. Indigenous strains used: perennial ryegrass 16 lb. per acre; cocksfoot 10 lb.; timothy 4 lb.; rough-stalked meadow grass ½ lb.; late flowering red clover 4 lb.; wild white clover 1 lb. Grazed during 1929.

Previous manuring. 6 cwt. per acre basic slag November 27th, 1928. 8 tons per acre farmyard manure December 5th, 1928. 1¼ cwt. per acre sulphate of ammonia early autumn 1929.

Plots: 10 yd. × 2 ft.; six replicates in six randomised blocks. All plots harrowed and rolled March 13th, 1930.

Treatments			
No.	Symbol	Date	Treatment
(1)	No N	Dec. 6th, 1929	No N
(2)	W. S/A	,,	0·4 cwt. N as W. S/A
(3)	W. S/A + dicy.	,,	0·2 ,, W. S/A 0·2 ,, W. dicy.
(4)	W. Cy.	,,	0·4 ,, W. Cy.
(5)	W. Cy. + dicy.	,,	0·2 ,, W. Cy. 0·2 ,, W. dicy.
(6)	S. S/A	Feb. 18th, 1930	0·4 ,, S. S/A

Individual cuts.

Date of cutting ...	Apr. 27	May 16	June 2	July 1	Aug. 19	Nov. 13
No. of replicates ...	5	6	6	6	3	6

Yield of dry matter, cwt. per acre.

Treatment						
(1) No N	2·41	3·29	3·14	4·51	3·19	1·57
(2) W. S/A	3·31	4·42	3·19	4·64	3·53	1·80
(3) W. S/A + dicy.	2·97	4·23	3·33	5·43	3·92	1·92
(4) W. Cy.	2·86	4·12	3·33	4·84	3·58	2·06
(5) W. Cy. + dicy.	2·68	4·01	3·37	4·80	3·76	1·82
(6) S. S/A	4·79	5·70	3·24	4·06	3·55	2·05
S.E.	0·138	0·195	0·083	0·192	0·303	0·112
S.E. as % of mean	5·14	6·28	2·56	4·00	8·46	6·00

Nitrogen, as per cent. of dry matter.

(1) No N	2·49	2·50	2·63	2·49	3·01	3·32
(2) W. S/A	2·66	2·49	2·71	2·39	2·94	3·42
(3) W. S/A + dicy.	2·60	2·52	2·79	2·49	2·92	3·52
(4) W. Cy.	2·60	2·55	2·74	2·49	2·98	3·34
(5) W. Cy. + dicy.	2·59	2·51	2·72	2·43	2·82	3·40
(6) S. S/A	2·91	2·50	2·72	2·25	2·74	3·19
S.E.	0·039	0·021	—	—	—	—
S.E. as % of mean	1·48	0·84	—	—	—	—

Totals for year.

	Yield of dry matter		Yield of nitrogen	
Treatment	Cwt. per acre	As % of no N	Nitrogen, cwt. per acre	As crude protein cwt. per acre
(1) No N	18·10	100	0·485	3·03
(2) W. S/A	20·89	115	0·561	3·51
(3) W. S/A + dicy.	21·81	120	0·594	3·71
(4) W. Cy.	20·79	115	0·567	3·54
(5) W. Cy. + dicy.	20·43	113	0·546	3·41
(6) S. S/A	23·38	129	0·624	3·90
S.E.	0·604	3·34	—	—
S.E. as % of mean	2·89	—	—	—

that the clover was less vigorous on the spring sulphate of ammonia plots than elsewhere. When the third cut was taken, at the beginning of June, the direct response of the herbage to nitrogen seemed to have disappeared, while during the rest of that month the suppression of clover became more and more evident. At the time of the fourth cut, on July 1st, the spring sulphate of ammonia plots could be picked out by anyone not knowing the lay-out of the experiment, because of the relative scarcity of clover flowers, and the effect showed strikingly in photographs. The reason for this action on clover will be considered later.

The effects of the different treatments on *yield of dry matter* (Table IV) accord with these observations. All the treatments except winter calcium cyanamide + dicyanodiamide, produced significant increases over no nitrogen in the first cut, and all of them did so in the second cut. By the third cut, however, the effect of the added nitrogen had been used up (in spite of the rather heavy dressing used), for there were no significant differences on June 2nd. In the last two cuts of the year the untreated plots tended to be below the others, although the difference only reached significance with three treatments in the last cut.

Spring sulphate of ammonia was by far the most effective treatment in the first two cuts, giving yields significantly above any others. In the July cut, on the other hand, the yield was significantly below that with most of the other treatments: this may be attributed to the poorer growth of clovers.

Winter sulphate of ammonia was rather less than half as effective as the spring dressing in the first two cuts. It showed, however, no depression in yield in July. *Winter Calcium Cyanamide* was not as effective as winter sulphate of ammonia in either of the first two cuts, although the difference was significant only in the first cut. Replacing half the nitrogen by *dicyanodiamide* gave lower yields with both forms of nitrogen in both of the early cuts, but none of the differences was significant. There appeared to be a significant delayed response to dicyanodiamide with sulphate of ammonia on July 1st; this was probably due to the increased development of clovers that was observed with this treatment.

Effects on clovers. After the July cut A. R. Clapham kindly estimated the area occupied by clovers under the different treatments (by graphical plotting). He found no significant differences between no nitrogen and any of the winter treatments, although there was an increase with winter sulphate of ammonia + dicyanodiamide that was on the verge of significance. Spring sulphate of ammonia caused a depression that was highly significant:

Treatment ...	No N	W. S/A	W. S/A + dicy.	W. Cy.	W. Cy. + dicy.	S. S/A	S.E.
Clover, % of total herbage by area	43·0	36·3	49·5	41·7	44·4	14·4	2·24

If the twelve plots in which half the nitrogen was present as dicyanodiamide are compared with the twelve plots which received a full dressing of nitrogen as winter sulphate of ammonia or calcium cyanamide, the result (without dicyanodiamide 39·0 per cent., with dicyanodiamide 46·9 per cent.) shows that there was a higher proportion of clovers with dicyanodiamide. Because of the greater number of plots involved the difference is highly significant.

These results throw some light on the reasons for clover repression with sulphate of ammonia. Possibly with a sufficiently heavy dressing, sulphate of ammonia is directly toxic to clovers, but in this experiment, although some damage to the clover foliage was observed shortly after the spring application, this disappeared. It was not until two cuts had been taken that a relative decrease in clovers became noticeable. This suggests that competition with the heavy growth of grass produced by the spring nitrogen was the chief factor in the reduction of clover.

The values for the percentage of clovers under different treatments in July show a tendency to an inverse relationship when compared with the effects of the treatments on yield in earlier cuts. Spring sulphate of ammonia gave higher yields than winter sulphate and caused a greater depression of clovers; treatments receiving dicyanodiamide gave lower yields than those without it, and higher clover percentages.

If actual treatments are neglected and the plot yields for the first two cuts (the duration of the response to nitrogen) are correlated with the percentage of clover in each plot in July, a correlation coefficient of $-0{\cdot}423$ is obtained. Since thirty-six plots are involved in the comparison this result is highly significant ($P = < 0{\cdot}01$). It shows that the greater the growth of grass in spring—the greater the competition for nutrients and light—the less was the growth of clover in summer.

Nitrogen content of herbage. For the first two cuts the percentage of nitrogen was determined on samples from individual plots. The standard errors were so low in comparison with those for yields, that subsequent determinations were made on a single bulked sample for each treatment.

The percentage nitrogen content in the first cut was greatly increased by spring sulphate of ammonia, and to a less extent, though still significantly, by winter sulphate. The effect of the other treatments was only on the verge of significance. In the second cut there were no significant differences, showing that, although some extra nitrogen was still present in the herbage, it was no more than could be efficiently utilised by the plant in producing dry matter. In later cuts the effect of clover repression is to be seen in the relatively low nitrogen values with spring sulphate of ammonia.

The apparent *recovery of added nitrogen* from the different treatments is complicated by the clover effect and the falling off in the yield of the no-nitrogen plots in autumn. Since, however, the direct action of the nitrogen on the herbage was exhausted in the first two cuts (when there was relatively little clover in the herbage), and the effect on the clover was most marked in the later cuts, the nitrogen taken up in the first two cuts may be used to measure the "recovery." This is done in Table IV, the corresponding figures for the whole year being given also for comparison.

Table IV. *Recovery of added nitrogen. Stackyard Field*, 1930.

	Recovery in first two cuts		Recovery over whole year	
Treatment	Cwt./acre	%	Cwt./acre	%
W. S/A	0·060	15	0·076	19
W. S/A + dicy.	0·045	11	0·109	27
W. Cy.	0·035	9	0·082	23
W. Cy. + dicy.	0·027	7	0·061	15
S. S/A	0·144	36	0·139	35
S.E.	0·0113	2·8	—	—

Because the nitrogen contents had been determined on separate plot samples for the first two cuts, the standard errors of the values for nitrogen taken up, and hence for nitrogen recovery, could be calculated. The corresponding data were not available over the whole year.

It will be seen that the recovery from spring sulphate of ammonia was significantly higher than that from any of the winter treatments, while none of the differences between the winter treatments was significant. There was no indication in the recovery from the first two cuts that calcium cyanamide or dicyanodiamide had enabled the herbage to secure more nitrogen in competition with winter leaching.

The "recoveries" for the whole year were somewhat higher, with the winter treatments, than those for the first two cuts. The significance of the difference cannot be estimated, and emphasis need not be placed on it. Spring sulphate of ammonia did not show it, while it was particularly marked with winter sulphate of ammonia and dicyanodiamide, so the clover effect may have been partly responsible. Since there was also a tendency, rarely reaching significance, for the no-nitrogen plots to give poorer yields than the others in the autumn, it is possible that a little of the added nitrogen locked up by micro-organic action in winter and spring became available in the autumn.

(*b*) *Stackyard Field experiment*, 1930–1.

After the last cut in 1930 sheep were allowed to graze the plots (in common with the rest of the field) for a month. The experiment was then repeated on the same plots, chiefly in order to examine under slightly different conditions the action of dicyanodiamide. In the second year this compound was applied as a dressing additional to a full application of nitrogen in the form of sulphate of ammonia or calcium cyanamide.

Because of snow and cold in early spring, the spring sulphate of ammonia was applied nearly a month later than in 1930.

The conditions were increasingly divergent from those of normal pasture, so the results from this year (Table V) will be considered in less detail than those of the previous year.

In the second year of the experiment the growth of clovers was remarkably abundant even at the time of the first cut, probably as a result, at least in part, of the repeated mowing of the previous year. The season was a late one, with a cold March, and this may also have checked the early growth of the grasses and given clovers an advantage. The clovers were fairly plentiful on the spring sulphate of ammonia plots (they had not been killed out), but they were far more dense on the others, especially on the no-nitrogen plots. The results must be examined with this in mind.

There was a significant response in yield to all forms of nitrogen in the first cut, but no significant responses in the second, at the beginning of June.

Spring sulphate of ammonia was not significantly above winter sulphate (alone or with dicyanodiamide added) in the yield of the first cut. In the third cut (early July) it was significantly below all other treatments: a more marked expression of the effect on clover observed in July of the previous year. The percentage nitrogen content of the herbage was below the no-nitrogen plots with spring sulphate of ammonia until the autumn, which must be attributed to the preponderance of clovers in the herbage of the untreated plots.

Table V. *Stackyard Field, yield and nitrogen content of herbage*, 1931.

Previous cropping, etc., see Table III. Grazed in late autumn of 1930. Same plots as in 1930.

Treatments. Nitrogen as sulphate of ammonia or calcium cyanamide, 0·4 cwt. per acre. Nitrogen as dicyanodiamide, Nos. 3 and 5, 0·2 cwt. per acre extra. Numbers and symbols (below) as in Table III.

Winter treatments applied December 10th, 1930.

Spring sulphate of ammonia applied March 13th, 1931.

Individual cuts.

Date of cutting ...	May 9	June 1	July 3	Aug. 7	Sept. 28	Dec. 11
	Yield, dry matter, cwt. per acre.					
Treatment						
(1) No N	5·76	10·49	9·96	7·54	8·44	1·90
(2) W. S/A	7·39	10·93	10·03	7·99	8·57	2·06
(3) W. S/A + dicy.	7·84	10·85	9·67	7·52	8·95	2·24
(4) W. Cy.	6·90	9·92	10·07	7·64	7·99	2·00
(5) W. Cy. + dicy.	6·60	10·02	9·67	7·34	8·43	2·01
(6) S. S/A	7·97	10·16	8·60	8·23	7·92	1·66
S.E.	0·264	0·167	0·226	0·235	0·348	0·104
S.E. as % of mean	3·73	1·60	2·33	3·05	4·15	5·34
	Nitrogen, as per cent. of dry matter.					
(1) No N	4·14	4·08	4·01	4·00	3·68	3·50
(2) W. S/A	3·88	3·76	4·01	4·09	3·50	3·57
(3) W. S/A + dicy.	3·95	3·68	3·96	3·82	3·69	3·54
(4) W. Cy.	3·72	3·79	3·89	4·06	3·50	3·62
(5) W. Cy. + dicy.	3·68	3·74	3·88	3·83	3·56	3·55
(6) S. S/A	3·35	3·33	3·80	3·93	3·78	3·49

Totals for year.

	Yield of dry matter		Yield of nitrogen	
Treatment	Cwt. per acre	As % of no N	Nitrogen cwt. per acre	As crude protein cwt. per acre
(1) No N	44·10	100	1·745	10·9
(2) W. S/A	46·97	106	1·800	11·2
(3) W. S/A + dicy.	47·07	107	1·789	11·2
(4) W. Cy.	44·53	101	1·687	10·5
(5) W. Cy. + dicy.	44·08	100	1·646	10·3
(6) S. S/A	44·54	101	1·613	10·1
S.E.	0·815	—	—	—
S.E. as % of mean	1·80	—	—	—

Winter sulphate of ammonia and *winter calcium cyanamide* showed greater differences in yield than in the previous season; if the twelve plots receiving each of these treatments (ignoring additions of dicyanodiamide) are compared, sulphate of ammonia was significantly better than calcium cyanamide in both of the first two cuts.

Adding *dicyanodiamide* to a full winter dressing of sulphate of ammonia or calcium cyanamide had no significant effect on the yield in any of the cuts. Taking the two seasons together, dicyanodiamide would seem to have been inert so far as its effect on yield of grass was concerned; it may possibly have been washed out of the soil by winter rains. Its formation when superphosphate is mixed with calcium cyanamide offers no advantage for the manuring of grassland.

In the last cut of 1931, as in 1930, the no-nitrogen plots gave a lower yield than any of the winter nitrogen plots, but the difference was only once significant. The yields in the last cut in both years were small, and if this result indicates that some of the winter nitrogen was being released late in the following autumn the effect was nevertheless almost negligible.

(c) *Sawyers Field experiment*, 1930–1.

The object of this experiment was to make a direct comparison between calcium cyanamide and sulphate of ammonia in both autumn and spring. The field was similar in its history to Stackyard Field (see Table VI), and was grazed—latterly by pigs and sheep—up to the beginning of the experiment. Plots were prepared and mown, and treatments were applied in the manner already described. Although rain fell soon after the autumn dressings were applied, the calcium cyanamide plots suffered damage which remained evident throughout the winter and probably influenced the yields obtained.

Because a cold spell was followed by drought, the spring dressings were withheld until rain came, which was not until the beginning of April. By this date the autumn sulphate of ammonia plots and to a less extent the calcium cyanamide ones were distinctly greener than the others. That is to say, there were signs of an "early bite" from the autumn nitrogen in a season when early application of spring nitrogen offered difficulties.

It was intended to alternate mowing and grazing in this experiment, in order to approximate more nearly to pasture conditions, but only one cut was actually taken. In consequence there was no opportunity to examine residual effects, but the results of the Stackyard experiment conducted at the same time suggest that the direct effects of the added nitrogen were largely measured in the first cut.

The results showed a significant response in yield to all treatments except autumn calcium cyanamide, while there was no significant difference between the yields with autumn and spring sulphate of ammonia, or between spring sulphate of ammonia and spring calcium cyanamide. Both spring treatments raised the percentage nitrogen content significantly, but the autumn dressings did not. In other words, the nitrogen taken up in the autumn was fully utilised by the plant in building up further dry matter.

Table VI. *Sawyers Field, yield and nitrogen content of herbage*, 1931.

Previous cropping. Seeds mixture sown under barley in April 1928. Indigenous strains used: 10 lb. perennial ryegrass, 8 lb. cocksfoot, 2 lb. timothy, 2 lb. meadow fescue, 2 lb. rough-stalked meadow grass, 1 lb. early-flowering and 2 lb. late-flowering red clover, 1 lb. wild white clover, 2 lb. chicory. Grazed during 1929 and 1930.

Previous manuring. 1½ cwt./acre sulphate of ammonia, autumn 1929; 1 cwt./acre sulphate of ammonia, spring 1930.

Basal dressing. Superphosphate = 0·4 cwt. P_2O_5/acre; sulphate of potash = 0·4 cwt. K_2O/acre; the potash was applied to only one-half of each plot.

Plots: 10 yd. × 1 yd.; five replicates in five randomised blocks.

Treatments: (1) No nitrogen.
(2) Autumn sulphate of ammonia, 0·4 cwt. N/acre, November 7th, 1930.
(3) Autumn calcium cyanamide, 0·4 cwt. N/acre, November 7th, 1930.
(4) Spring sulphate of ammonia, 0·4 cwt. N/acre, April 2nd, 1931.
(5) Spring calcium cyanamide, 0·4 cwt. N/acre, April 2nd, 1931.

Cut. April 30th, 1931.

Treatment	Yield dry matter cwt./acre	Nitrogen % in dry matter	Nitrogen in herbage cwt./acre	Recovery of nitrogen cwt./acre	%
(1) No N	10·0	3·60	0·360	—	—
(2) A. S/A	13·2	3·60	0·475	0·115	29
(3) A. Cy.	10·4	3·56	0·370	0·010	2
(4) S. S/A	13·0	3·96	0·515	0·150	38
(5) S. Cy.	12·2	3·83	0·467	0·107	27
S.E. actual	0·34	0·052	—	—	—
S.E. as % of general mean	2·8	1·4	—	—	—

The plots were halved for potash, but there was no significant response to potash, either over the whole experiment or in interaction with the nitrogen treatments.

The recovery of nitrogen from the different treatments showed that the autumn dressings were less efficient than the spring ones, although with sulphate of ammonia the difference was not great. The recovery from spring calcium cyanamide was less than from sulphate of ammonia, but again the difference was not very large; in view of the short period—4 weeks—between application and cutting this may be taken as indicating quite rapid availability of the cyanamide nitrogen.

DISCUSSION.

The lawn-mowing technique. A full examination of the advantages and disadvantages of this method of studying grassland problems would require more space than is available here. Obviously it will tend to cause changes in the mixed herbage different from those ensuing under controlled grazing. At the same time it keeps the herbage in the immature condition, and to this extent it approximates more nearly to intensive grazing than to meadow conditions.

The method of repeated mowing represents, indeed, an intermediate stage between pasture and meadow. Whereas the herbage is maintained in the immature state, the plant nutrients it contains are completely removed from the land instead of being partly returned. The most important bearing of this on the present work is that under grazing the return of much of the nitrogen in excreta would have prolonged the effect of the manures beyond that observed with mowing.

Since the experiments were laid out on pasture fields which were grazed until shortly before the work began, the first cut or two taken with the mower may fairly be regarded as representative of pasture conditions.

For exploring the behaviour of nitrogenous fertilisers the lawn-mowing technique offers definite advantages. By its means a replicated experiment is readily carried out, and considerable accuracy is obtained (as may be seen in the low standard errors of yields in the present experiments). Measures of the duration of the direct effect of the nitrogen, and of the nitrogen recovery in the early cuts, are possible precisely because there are no animals to complicate the results. Further, if the direct recovery of added nitrogen in the herbage is worse from one treatment than from another, grazing stock may lengthen the period over which the nitrogen acts, but they can hardly increase the relative recovery from the poorer treatment.

Results obtained by this technique are directly applicable to the production of grass for artificial drying, by repeated mowing, a branch of agriculture which is now being developed in some parts of the country.

The behaviour of nitrogen in grassland soils. Conclusions from this and some more recent work have been briefly reviewed elsewhere (Richardson (5)). It will be sufficient to point out here that the ammonia level tends to be higher, relative to the nitrate level, in grassland soils than in arable ones. A similar result has been recorded by Eggleton, Lewis and Page (6) and by Penman (7). This higher ammonia level is probably attributable to less vigorous nitrifying activity in the undisturbed soil of grassland, since the extra ammonia disappears from many of the soils when they are allowed to nitrify under optimum conditions in the laboratory.

Other grassland soils nitrify poorly even in the laboratory, especially if their reaction is much on the acid side. In some of these it has been shown (Richardson (4)) that although added ammonia disappears rapidly when the grass is growing it remains in the soil if the herbage is removed. Clearly, as Hall, Miller and Gimingham (8) suggested many years ago, grass can take up its nitrogen directly as ammonia without the need for preliminary nitrification. Even in non-acid grassland soils, since nitrification is relatively less vigorous than in arable soils, it is likely that much of the nitrogen added in a dressing of an ammonium salt is taken up directly in this form, although a part may also be absorbed as nitrate.

In the present experiments the relatively rapid disappearance of ammonia and very slight production of nitrate in both winter and early spring suggested that ammonia was being taken up directly. However, the greater part of the nitrogen added did not appear in the herbage at all (less than 40 per cent. was recovered in any experiment). While there may have been some loss in the winter from leaching (which was shown—Crowther and Richardson (2)—to cause a fairly rapid loss of winter nitrogen from arable soil), this would not account for the loss when the grass was beginning to grow rapidly in the spring. It seems most probable that the poor recovery of added nitrogen was due to competition between the grass roots and those micro-organisms engaged in breaking down carbohydrates and building up nitrogenous organic matter in the soil.

It is common knowledge that old grassland soils are much richer in nitrogenous organic matter than are corresponding arable soils: this nitrogen becomes available when the soils are ploughed up. Presumably the loss of nitrogen in these experiments represents the other side of the picture: a "locking up" of nitrogen in young grassland soils. Later cuts showed that a little of this nitrogen became available in the autumn, but most of it remained in the soil.

Management and protein production. On this young grassland the conversion of added nitrogen into protein was rather inefficient. Although enough nitrogen was added to give 2·5 cwt. per acre of crude protein, during the first season on Stackyard Field only 0·9 cwt. per acre of additional crude protein was produced from the spring sulphate of ammonia dressing. This low figure was not entirely due to clover suppression, since similarly low recoveries of nitrogen were obtained in the early cuts on both Stackyard and Sawyers Fields.

The effect of the suppression of clovers was more marked in the second year of the Stackyard experiment. When the spring sulphate of ammonia treatment was repeated the total production of crude protein in the second season was actually less by 0·8 cwt. per acre than on the plots without nitrogen. In both years, also, the yields were depressed in July by the spring sulphate of ammonia.

In ordinary farming some suppression of clovers is likely to occur after heavy spring dressings of nitrogen, and in estimating the practical value of these dressings due attention should be paid to the probable depression in yield of herbage and especially of clovers and protein during the summer. Under some conditions of farming the "early bite" may be so important that summer keep may with advantage be sacrificed.

With careful management, however, the depression of clovers may be made much less than it was in these experiments. Here the clover undoubtedly suffered from competition with the vigorously growing grasses, during the rather long intervals between cuts. This might have been reduced by more frequent cutting on the manured than on the unmanured plots. Martin Jones has demonstrated that, by suitable control of the grazing and resting of pastures, either grassy or clovery swards may be produced almost at will. Further, he has shown (9) that with suitable management relatively heavy manuring with nitrogen need not disturb the balance between the competing species.

The influence of different nitrogenous manures on yield of herbage. Bringing together the results of the three experiments, spring applications of nitrogen always secured a good immediate response, but it lasted for only one or two cuts. In the spring calcium cyanamide was practically as effective as sulphate of ammonia.

Winter (December) applications gave a measurable response, but much less than the spring dressings. Over the whole year they appeared to more advantage because they caused less suppression of clovers.

Late autumn (November) sulphate of ammonia proved better than the December applications and almost as good as a spring one, probably because the grass was not yet dormant and secured enough nitrogen to give it a good start in spring. Calcium cyanamide applied at this time caused more injury than in December (when the grass was dormant) or in spring (when vigorous fresh growth soon repaired any injury that occurred).

Concerning *calcium cyanamide*, and *dicyanodiamide*, these experiments have not shown any advantage attributable to the supposed slow availability of the nitrogen. Under favourable spring conditions, as the Sawyers' experiment showed, cyanamide nitrogen is nearly as rapidly available as that of sulphate of ammonia. When cyanamide nitrogen is applied in late autumn or winter it checks the herbage, and puts the plant at a disadvantage in its competition with leaching or soil micro-organisms; the recovery of the herbage in spring comes too late for the best use to be made of the nitrogen.

SUMMARY.

1. Ammonia added as sulphate of ammonia disappeared rapidly from a pasture grassland soil, while very little nitrate accumulated. In winter or early spring three-fourths of the added nitrogen had gone in less than 4 weeks. After the first fortnight there was little difference in the soil inorganic nitrogen from calcium cyanamide and from sulphate of ammonia. A moderate dressing of dicyanodiamide slightly reduced but did not inhibit nitrification; it did not appreciably retard the disappearance of inorganic nitrogen from the soil in winter.
2. Winter applications of sulphate of ammonia produced less increase in yield or nitrogen content of repeatedly mown herbage than did spring ones. A late autumn application was almost as effective as a spring one. Calcium cyanamide in late autumn or early winter was on the whole less effective than sulphate of ammonia, but in spring the two were substantially equal. There was little evidence that calcium cyanamide was "slow acting" in comparison with sulphate of ammonia. Dicyanodiamide was practically inert so far as the effect of winter dressings on yield or nitrogen uptake was concerned.
3. Under repeated mowing the response of the herbage to a 2 cwt. dressing of sulphate of ammonia (or other nitrogenous fertiliser) was rapidly exhausted. Later in the year there was a reduction in yield with spring sulphate of ammonia, resulting from a depression of clovers in summer through competition with the heavier growth of grass in the spring.
4. The recovery of added nitrogen in the herbage was, at best, less than 40 per cent. This may have been due in part to its locking up by microbiological action in the soil organic matter.

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A COMPLEX PIG-FEEDING EXPERIMENT.

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(With One Graph.)

INTRODUCTION.

In the last ten years there has been something of a revolution in agricultural experimental technique, as far as field crops are concerned, but it is only lately that the new methods have begun to spread to live-stock experimentation. It is likely that a similar improvement will be witnessed here also, both in the efficiency of experimentation, and in the validity of the results obtained, but there are many problems which require investigation before a technique which is not only logically and statistically sound but also reasonably efficient can be evolved.

The farm of the Rothamsted Experimental Station has for the last few years bred pigs fairly extensively. This activity was undertaken largely for commercial reasons in order to make efficient utilisation of products of the arable part of the farm which is necessary for the main experimental work of the station. It has, however, been the practice to record the growth of these pigs, and the Farm Director has, for his own information, from time to time undertaken a few simple experiments. The opportunity was thus to hand of making investigations in problems of animal husbandry and management at little cost, and in the summer of 1933 an experiment was started with a view to utilising the available material and contributing towards the solution of problems of experimental technique.

The animal nutrition station at Cambridge has for some time been working in the same field, and a paper by Dunlop has recently been published in this *Journal* (2), which gives an account of the methods adopted by that station and also contains an able review of previous work by other stations, both in this country and abroad. The Cambridge work, which was undertaken independently of that at Rothamsted, forms a most interesting parallel, and comparison of the similarities and differences of the methods adopted at the two stations will serve to bring out the experimental problems involved.

In this paper we propose to review the first Rothamsted experiment, which is now completed, and then to make a comparison of the methods adopted with those of Cambridge. Finally a short discussion of possible lines of improvement will be given.

REQUIREMENTS OF A GOOD EXPERIMENTAL TECHNIQUE.

The first and perhaps the most important requirement of any method of experimentation is that the experiments should be so designed and executed that it is possible to draw sound inferences from the results. This is one of the objects of replication and the sole object of randomisation in experiments on field crops, and similar processes must be adopted in other types of experiment if the inferences are to escape criticism of a type which is difficult to refute. An animal husbandry experiment, for example, in which all the animals on one treatment are confined to one pen, and all the animals on the other to another pen, is always open to the objection that the pen of the less successful treatment was less favourably placed, or that the animals of this pen developed some disease, and the experimenter can only express his personal opinion that this was not in fact the case. Statistically we say that a valid estimate of error is required, that is, an estimate which is unbiased and includes all sources of error which affect the results, *and no others.*

The experiment described in this paper itself provides a striking illustration of the paramount importance of this requirement. Here many of the pigs without green food (one of the experimental treatments) became sick. There is no doubt that this sickness, whatever it was, was conditioned by lack of green food, but had the pigs without green food all been run in one pen or group of pens it is very probable that the sickness would have been attributed to extraneous causes, and its association with green-food deficiency overlooked, especially in view of the fact that previous experiments on green food at Rothamsted had indicated that pigs did not require this addition to their diet. In any case the conclusions drawn would have been subject to a very large element of doubt, and would by themselves have been of little or no value.

The second requirement is that the inferential basis of the results should be as wide as possible, that is, as many as possible of the types of material and combinations of circumstances over which the conclusions are intended to apply should be included. Thus a conclusion as to the nutrient value of a certain feeding stuff is definitely strengthened if more than one breed and other factors such as amount of exercise are included in the experiment. This is one of the arguments in favour of the complex type of experiment which is proving so useful in agricultural field experimentation.

Thirdly, the technique must be efficient, that is, it must make the best use of the material and labour available. The complex type of experiment stands out as one of the most powerful methods of increasing efficiency.

Fourthly, the results must be capable of analysis by the available statistical methods. Improvement in statistical methods often suggests radical changes of design. For many purposes also it is important that the results should be capable of easy interpretation by those unversed in statistical procedure; this consideration sometimes, though perhaps not so often as is thought, conflicts with the requirements of efficiency.

It will be obvious, to those acquainted with the parallel fields of agricultural experimental technique on crops and live stock, that the methods of the former far surpass those of the latter when judged on the above standards. The complex type of experiment has scarcely as yet been applied to live stock, and the great majority of live-stock experiments provide an estimate of error which is of doubtful value.

The chief difference between crop and live-stock experiments which might account for this is the mobility in the material of the latter. A treatment, whatever its nature, once applied to a plot, only affects the plants on that plot, but in any feeding trial with animals different feeding can only be given by separating the animals at feeding time. This offers a strong inducement to run all animals on the same food in the same pen. Such communal feeding not only precludes any valid estimate of error but also prevents any wide variety of different feedings, since the number of these is limited by the number of available pens.

The obvious solution is individual feeding. Such feeding has the additional advantage of enabling the food consumption of each animal to be recorded. It is also likely to induce a more even growth by eliminating competition at feeding time; though such elimination, inasmuch as it departs from ordinary practice, cannot be regarded as wholly advantageous.

The difficulty of individual feeding varies widely according to the live stock to be experimented on, and the type of experiment. With animals fed indoors there is only the problem of providing suitable pens. Grazing experiments, on the other hand, present almost insuperable difficulties.

In one other respect most experiments with animals differ greatly from experiments with annual field crops. In experiments with animals the weight of any particular animal at the beginning of the experiment usually provides a valuable measure of the potential development of that animal.

The methods of utilisation of this information (or the parallel information of previous cropping in a perennial crop) provide an excellent illustration of the way in which improvement in statistical method may radically affect the design. Prior to the introduction of the analysis of covariance it was customary either to balance out the weights, *i.e.* assign animals as nearly as might be of equal total weight to each treatment, or group animals of nearly equal weight together and assign one or more from each group to each treatment. The former method makes any estimate of error impossible (except by an analysis of covariance), while the latter method, though useful and capable of yielding statistically valid results, introduces another set of restrictions into the design, and becomes progressively less efficient as the number of treatments is increased. The analysis of covariance enables the effects of differences in initial weight to be eliminated without any account being taken of them in the initial design. It thus gives greater freedom of design which can be utilised for other purposes.

THE ROTHAMSTED EXPERIMENT.

The Rothamsted experiment was designed to test the performance of pigs from weaning to bacon weight when fed on dry and on wet meal, with or without the addition of green food. The effect of varying the numbers in a pen was also tested, equal floor space being assigned to each pig.

Table I shows the arrangement. The experiment was in three blocks. Each block contained twenty-four pigs, six from each of four litters, with as far as was possible equal numbers of hogs and gilts from each. Each block was subdivided into three, to give one pen of eight, two pens of four, and four pens of two, the position of each sub-block within the block being determined by random choice. In each sub-block there were two pigs on each of the four feeding treatments. Sex and litter were equalised as far as possible over the various treatments, pigs of given sex and litter being allotted to their assigned treatments at random.

The composition of the meal is shown in Table II. This was varied from time to time to suit the needs of the growing pig. The introduction of bran was made on account of the low quality of the middlings available during the latter half of the experiment.

The pigs were weighed weekly, before the afternoon feed. The food consumption was also recorded weekly, each pig being fed from its own bag. Feeding was *ad lib.*[1] twice daily, 7 a.m. and 3 p.m. Any small amounts of wet food left unconsumed at the end of the week were weighed and discarded. Dry food was returned to the bags.

Table I. *Arrangement of experiment.*

Block and duration ...	Block I (21 weeks)								Block II (22 weeks)								Block III (20 weeks)							
Litter No. ...	9		12		19		21		17		20		29		48		27		28		35		58	
Age at start (weeks) ...	7·9		10·9		13·6		12·0		9·7		11·7		11·3		12·1		8·1		10·4		10·7		12·6	
Sex	H	G	H	G	H	G	H	G	H	G	H	G	H	G	H	G	H	G	All	H	All	G	H	G
Dry and green food	8	2	2	8	.	4	4	.	8	.	4	2	.	8	2	4	.	2	8	4	8	4	2	.
Wet and green food	.	4	4	.	2	8	8	2	2	4	.	8	4	2	8	.	4	8	2		2		8	4
Dry food	4	.	.	4	2	8	8	2	2	4	.	8	4	2	8	.	4	8	2		2		8	4
Wet food	8	2	2	8	4	.	.	4	.	8	4	2	8	.	2	4	.	2	8	4	8	4	2	.

The number 2, 4 or 8, indicates that the pig was one of a pen of 2, 4 or 8 respectively.
H denotes hog (*i.e.* castrated male), G denotes gilt (*i.e.* female).

Table II. *Composition of feeding rations.*

	Weeks of experiment			
Block I ...	1–3	4	5–18	19–21
„ II ...	1–3	4	5–14	15–22
„ III ...	1–3	4	5– 9	10–20
	Percentage rations			
Middlings	60	50	40	28
Bran	—	—	—	14
Hominy chop	—	15	20	18
Barley meal	20	25	30	30
Flaked maize	10	—	—	—
Fish meal	10	10	—	—
Meat meal	—	—	10	10

Two per cent. minerals (3 parts lime, 1 part salt) added to each ration.
Green food (kale, wheat, oats and vetches) fed twice daily at the rate of about ½ lb. per head per day.

The pens were stoutly constructed of 1 in. deal boarding, with partitions 2 ft. 6 in. high. The dimensions of the pens (excluding the feeding pens) were as follows:

Pens of eight: 13 ft. × 6 ft. 3 in.
Pens of four: 6 ft. 6 in. × 6 ft. 3 in.
Pens of two: 3 ft. 3 in. × 6 ft. 3 in.

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[1] This expression, as here used, does not denote constant access to the food supply at all times, but merely unlimited food supply at feeding times. Similarly *rationing* is used to denote restricted food supply at feeding times.

The feeding pens were 1 ft. 8 in. × 3 ft. 7 in. They were fitted with drop doors and each contained a small zinc feeding trough. One side of each feeding pen was of chain link netting, so that the pig could see its neighbour feeding. One of each four pens was arranged as an entrance to the main pen. Water was available in one of the feeding pens except at feeding time. The feeding pens were contiguous to the gangway between the blocks in the same manner as the Cambridge lay-out. The floor was concreted.

The pens occupied a corner of a large building whose two adjacent sides were of corrugated iron. There was a loft above, but in spite of this the temperature conditions were very variable, and during the hot spell of the summer of 1933 it was thought that the pigs were doing badly owing to the heat. Subsequent examination of the records, however, revealed that only the pigs without green food were affected.

The pigs themselves were not all the same breeding. One litter in each of the first and third blocks were pure Wessex, and the rest were by a Large White boar out of either a Wessex or Large Black sow.

METHOD OF ANALYSIS APPROPRIATE TO COMPLETE RESULTS.

We now propose to discuss the methods of analysis appropriate to the design adopted. The design at first sight appears somewhat complex, but from what follows it will be seen that with a full set of data the analysis is extremely simple.

Each block is complete in itself, in the sense that it is equalised as far as possible for sex and litter. An error can be computed for each block separately. Examining block I in detail, we observe that as many pigs of each litter and of each sex receive dry food as wet food; the same holds for green food, and for the numbers in a pen. The interaction between wet (W) and dry (D) feeding and green food (G), however, is not equalised for litters. If it were equalised it would be computed from the expression

$$Q=\tfrac{1}{6}\,S\,(WG-DG-W+D),$$

and this has two pigs of litters 19 and 21 in excess and two litters of 9 and 12 in defect. This expression therefore needs a correction for litter effects. The exact form of the correction can be obtained by fitting constants; if $S\,(L)$ represents a litter total the corrected estimate is found to be

$$Q'=\tfrac{3}{16}\,[S\,(WG-DG-W+D)+\tfrac{1}{3}\,S\,(L_9)+\tfrac{1}{3}\,S\,(L_{12})-\tfrac{1}{3}\,S\,(L_{19})-\tfrac{1}{3}\,S\,(L_{21})].$$

It is obvious by inspection that the litter effect is now eliminated.

In the analysis of variance the sum of squares appropriate for testing this interaction will be $\frac{4}{3}Q'^2$, since the variance of Q' is $\frac{3}{4}$ that of a single pig. The estimate of error variance may be obtained by deducting from the total sum of squares the sum of squares for litter (estimated as usual from the litter totals), sex, numbers in pen, wet *v.* dry food, green food and the interaction of these last (calculated from the above formula). Note that since litters are partially confounded with the treatment interaction the litter sum of squares here obtained is not the appropriate one for testing litter effects.

There is left in error the interactions of numbers in pen with the feeding treatments. The two main interactions could if desired be taken out in the ordinary manner. The second order interaction, however, is partially confounded with litters; its extraction from error would therefore be more difficult. The above estimate of error also involves the assumption that the sex difference is substantially constant from litter to litter, so that the interaction of sex and litters may be considered as pure error. It will also be realised that numbers in pen is analogous to sub-blocks, and the ordinary experimental error is therefore not appropriate for numbers in pen comparisons.

Blocks II and III are similar in design to block I with the exception that in neither case were four litters with three hogs and three gilts available. In the arrangement adopted sex is no longer orthogonal with litters (but is still orthogonal with treatments). The analysis is again quite simple. The sum of squares for sex for block II is given by

$$\tfrac{3}{68}\{S(H)-S(G)+\tfrac{1}{3}S(L_{20})-\tfrac{1}{3}S(L_{48})\}^2,$$

and for block III by

$$\tfrac{3}{32}\{S(H_{27})+S(H_{58})-S(G_{27})-S(G_{58})+\tfrac{1}{3}S(L_{27})-\tfrac{1}{3}S(L_{58})\}^2,$$

where $S(H_{27})$ indicates the sum of the hogs of litter 27, etc. It will be realised that these are the sums of squares that are to be subtracted from the total sum of squares to give the error, but they are now no longer appropriate for testing sex effects.

In order to see how the experiment was going a preliminary analysis of block I was undertaken after it had been running for six weeks. Table III gives the initial weights and the weights after six weeks. Table IV gives the analysis of variance of the initial and experimental weights, the corresponding analysis of covariance, and the analysis of variance of the experimental weights with the effects of varying initial weight eliminated. At the bottom of Table IV is given a summary of the treatment effects, adjusted for initial weight, together with their standard errors.

Table III.

Block I initial weights (lb.) (mean weight: 35·0 *lb.).*

	9 H	9 G	12 H	12 G	19 H	19 G	21 H	21 G	Total
DG	21	24	37	25	—	45	40	—	192
WG	—	28	29	—	47	50	30	37	221
D	26	—	—	30	60	39	38	29	222
W	24	30	25	27	61	—	—	37	204
Total	153		173		302		211		839

2's, 289; 4's, 296; 8's, 254; H, 438; G, 401.

Block I weights after six weeks (lb.) (mean weight: 68·6 *lb.).*

	9 H	9 G	12 H	12 G	19 H	19 G	21 H	21 G	Total
DG	31	46	75	45	—	80	76	—	353
WG	—	58	60	—	116	103	82	93	512
D	52	—	—	55	98	65	84	39	393
W	35	54	46	54	116	—	—	83	388
Total	276		335		578		457		1646

2's, 567; 4's, 580; 8's, 499; H, 871; G, 775.

Table IV. *Analysis of variance, block I. Initial weights and experimental weights after six weeks.*

	Degrees of freedom	Sums of squares and products (In.)^2	In. × Exp.	(Exp.)^2	(Exp. $-b$ In.)^2	Mean square	
Company	2	126·58	+ 244·70	473·08	0·92	0·46	
Wet *v.* dry	1	5·04	+ 70·58	988·17	724·03	724·03	(− 8·51)
Green food	1	7·04	− 45·50	294·00	506·12	506·12	(− 8·27)
W × *G*	1	11·02	− 16·29	24·08	134·58	134·58	
Litters	3	2180·46	+ 4319·58	9000·84	446·37	148·79	
Sex	1	57·04	+ 148·00	384·00	19·06	19·06	
b	1	423·78	+ 854·51	2905·67	1723·02	1723·02	
Error	13				1182·65	90·97	
Total	23	2810·96	+ 5575·58	14069·84			

Increase in experimental weight per lb. of initial weight (b) = + 2·0164 lb.
Interaction $W \times G$ (Q'): In. = − 2·875 lb.; Exp. = 4·25 lb.; Exp. − b In. = + 10·05 lb. ± 8·24 lb.
Increase per pig due to wet as against dry feeding (adjusted for initial weight)

$$= \tfrac{1}{12}(512 + 388 - 353 - 393) - b\,\tfrac{1}{12}(221 + 204 - 192 - 222) = 10{\cdot}98 \text{ lb.} \pm 3{\cdot}89 \text{ lb.}$$

Increase per pig due to green food (adjusted for initial weight) = 9·18 lb. ± 3·89 lb.

In testing the significance of treatment effects after elimination of differences of initial weight the comparison of the treatment mean squares derived from the analysis (Exp. $-b$ In.)^2 with the error mean square by means of the z test is not strictly correct, since the corresponding degrees of freedom are not orthogonal with the regression (b) degree of freedom. Fisher deals with this point (and the parallel disturbance to the standard errors) in (3), where he gives an elegant method of computing the correct treatment mean square. Alternatively, the appropriate corrections to the treatment mean squares of the analysis of (Exp. $-b$ In.)^2 can be obtained. If E_{xx}, T_{xx}, are the sums of squares in the analysis of the initial weights for error and the treatment group to be tested (n_t D.F.) respectively, and T_{xy} is the corresponding treatment sum of products, b being the ordinary estimate of the regression coefficient, the correction to the treatment *mean* square is

$$-\frac{(T_{xy}-bT_{xx})^2}{n_t(E_{xx}+T_{xx})}.$$

Since this correction is always negative there is no need to trouble with apparently non-significant effects. With a reasonable number of degrees of freedom for error it is usually small and can be computed on a slide rule. In the analyses of this paper the corrections are given in brackets. All are quite negligible.

There are several points of interest in the analysis under consideration. The pigs on wet food already show a significantly greater live-weight gain than those on dry food. Green food is also significantly beneficial, though the full effects of lack of green food are not yet apparent. The interaction between the feeding treatments is not significant. The difference between litters, which is very large (being chiefly an age effect), is nevertheless almost eliminated by allowing for initial weight. Variation due to both sex and numbers in pen (sub-blocks) is subnormal.

The error variance has been reduced to less than half its original value by the elimination of initial weight. The standard error per pig is 9·5 lb., which is 13·9 per cent. of the final weight or 28·4 per cent. of the increase in weight. These values are undoubtedly inflated by the imminent failure of pigs without green food, and by the fact that the obviously weakly hog of litter 9 on dry and green food was not excluded. But even without these causes a relatively high percentage standard error is of course to be expected when only a few weeks are taken, for temporary disturbances at the start of the experiment, and small irregularities in the growth rate, assume a much greater importance.

ANALYSIS AND DISCUSSION OF FINAL RESULTS.

The most striking, and disconcerting, feature of the experiment was the failure of pigs without green food. Of the thirty-six pigs without green food thirteen were removed from the experiment before its completion and fifteen of the twenty-three remaining lost weight during two or more weeks (not necessarily consecutive). Of the thirty-six pigs receiving green food only three (all on dry food) were removed from the experiment, and four more (two on dry, two on wet food) lost weight during two or more weeks. The pigs without green food would probably have done even worse but for the circumstance that pigs not thriving were run out in the fields for a day or two, so that any green-food deficiency was doubtless temporarily made up. No specific disease was detected, but clearly green food is a vital necessity to the health of pigs kept under these conditions.

The failure of the pigs which received no green food necessitated their rejection from the analysis of the final weights. This would have made the final analysis very troublesome were it not that both sex and numbers in pen proved to have an entirely negligible effect.

Table V exhibits the comparisons between pigs of opposite sex but of the same litter and feeding treatment. The final difference after correcting for initial differences by means of the regression coefficient determined later is only +1·41 lb., with a standard error (also determined later) of ±6·04 lb. There is thus no trace of any sex difference.

Table V. *Differences due to sex. Pigs in same litter and receiving same feeding.*

Live weights (lb.): hogs (♂) *minus* gilts (♀).

	Initial	Final	Final − *b* Initial
	+12	+76	+31·8
	− 3	− 3	+ 8·0
	− 7	− 7	+18·8
	+ 3	−20	−31·0
	− 8	−34	− 4·5
	− 3	− 3	+ 8·0
	+15	+34	−21·2
Mean	+ 1·3	+ 6·1	+ 1·41 ±6·04

Variation of numbers in pen likewise showed no effects. The elimination of any such effects in the analysis is not complicated by the failure of pigs without green food, but it is made more difficult by the failure of some of the pigs receiving green food. It was therefore omitted from the first analysis and its magnitude examined with the aid of the results obtained. No differences were discovered, and no adjustment of the first analysis was made.

It should perhaps be mentioned here that ignoring factors the effects of which the experiment was designed to eliminate, merely because no such effects appear to exist, will produce estimates of error which are biased, being on the average too small. Such a procedure should be adopted only in exceptional cases where the original design has more or less broken down.

With the neglect of sex and of numbers in pen the analysis of the pigs receiving green food becomes exceedingly simple. It may best be illustrated on the initial and final weights of block I. These are shown in Table VI.

In any litter having a single pig on wet feeding and a single pig on dry feeding the estimate of the feeding difference is merely the difference of the weights of the pigs. If there are two pigs on dry feeding the corresponding estimate is the difference of the mean of the weights of these two pigs and the weight of the pig on wet food, and similarly with two pigs on wet feeding. These differences are shown in Table VI together with their relative weights. The weighted mean of these differences gives the efficient estimate of feeding difference.

Table VI. *Initial and final weights of pigs on green food, block I.*

	Initial				Final			
Litter	9	12	19	21	9	12	19	21
Dry	24	37 25	45	40	151	218 142	191	205
Wet	28	29	47 50	30 37	194	190	229 232	205 212
$W-D$	+4	−2	+3·5	−6·5	+43	+10	+39·5	+3·5
Relative weight	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
Weighted mean	−0·533				+22·733			

In the analysis of variance the feeding effect is represented by the square of this weighted mean multiplied by the sum of the relative weights. The error can be estimated from two sources: (*a*) differences between the estimates of the treatment difference from the various litters, for which the sum of squares is computed by multiplying the square of each estimate by its relative weight, summing, and subtracting the feeding effect square already calculated; (*b*) differences between pigs in the same litter and on the same feeding, for which the sum of squares is computed by taking half the square of each such difference and summing.

This is the whole process of analysis. The results, as far as block I is concerned, are shown in Table VII, where the analysis with effect of initial weight eliminated is also given.

The results from the three blocks can be combined into one analysis, provided that we are prepared to assume that the error variance is constant from block to block. This does in fact appear to be substantially the case, and the assumption was therefore made. No pigs were rejected, other than those already rejected by the farm staff, except two pigs of the same litter of block III. These two pigs were both receiving wet food, and the dry-food pig had already been rejected.

The three estimates of the regression of final on initial weight from the three blocks are not significantly different. The values are shown in Table VIII. The combined estimate, 3·68, was therefore adopted in the adjustment of the final results for differences of initial weight.

Table VII. *Analysis of variance and covariance, block I. Sums of squares and products.*

	Degrees of freedom	(Initial)^2	Initial × final	(Final)^2
Treatment	1	0·71	− 30·31	1292·01
Error (*a*)	3	46·29	189·98	747·49
(*b*)	3	101·00	475·00	2917·00
Total error	6	147·29	664·98	3664·49

Regression of final on initial weight (b) = +4·5148.

Analysis of variance of final weight adjusted for differences of initial weight.

	Degrees of freedom	Sum of squares	Mean square	
Treatment	1	1580·17	1580·17	(−7·59)
Error	5	662·26	132·45	

Table VIII. *Summary of results.*

	Block			Mean or total
	I	II	III	
Number of pigs rejected	1	1	3	5
Time (weeks)	21	22	20	21
Commenced	Apr. 11	May 10	June 15	—
Average age at start (weeks)	11·1	11·2	10·5	10·9
Average weight (lb.): at start	35·6	32·9	41·2	36·6
at end	197·2	178·4	180·1	185·2
Regression of final on initial weight	4·51	3·52	2·81	3·68
Standard error	±0·930	±1·59	±0·985	±0·623
Increase per pig per week (lb.):				
Mean of wet and dry	7·70	6·61	6·94	7·08
Difference ($W-D$)	+1·18	+1·23	+2·47	+1·63
Standard error	±0·339	±0·324	±0·398	±0·205
Food per 1 lb. increase (lb.):				
Mean of wet and dry	4·306	4·596	4·504	4·469
Difference ($W-D$)	+0·334	+0·196	−0·159	+0·124
Standard error	±0·234	±0·234	±0·262	±0·141

The standard errors of the final weight of a single pig after adjusting for initial weight (16 degrees of freedom) was found to be 11·3 lb., which is 7·6 per cent. of the average increase in weight.

We are now in a position to consider the effect of wet *v.* dry feeding.

Wet feeding produces significantly greater increases of weight than dry feeding. The mean increases per pig per week for the three blocks, after adjustment for initial weight, are given in Table VIII. The pigs grew at decidedly different rates in the three blocks, and the difference between wet and dry feeding is significantly greater in the third block than in the other two.

This difference between wet and dry feeding is easily explicable. The pigs found the wet food more appetising, and consumed more of it. The mean food consumption per 1 lb. live-weight increase for the three blocks (given in Table VIII) is greater for the wet feeding in the first two blocks, but there is a reversal of the difference in the third block and none of the differences approaches significance. The efficiency of food utilisation, therefore, was substantially the same for wet and dry feeding.

The effect of dry feeding, consequently, is likely to be similar to that of rationing.[1] If there is no more efficient utilisation of the food with rationed feeding then clearly *ad lib.* feeding will be the most profitable, for it is both less trouble and enables a quicker turnover of pigs to be made, with a consequent reduction in overhead expenses, labour charges, etc.

General considerations would indicate that the faster the pig grows the smaller will be the proportion of the digested food required for maintenance. Consequently unless a considerable fraction of the food is undigested in *ad lib.* feeding it would appear that this system of feeding is likely to be the most efficient. The preliminary results of a further experiment now in progress, which is designed to investigate the effects of rationed feeding, confirm this argument, showing the highest efficiency with *ad lib.* feeding.

The above analysis depends on the assumption that numbers in pen have no appreciable effect. We can now demonstrate that this is the case. Table IX shows the final weights of block I set out by litters and numbers in pen. In litter 9 the pig with eight in pen is missing. The weights of the other pigs with eight in pen have therefore been adjusted by one-half the estimated difference per pig between wet and dry feeding for this block, or 11·37, this being added to the weights of those receiving dry food, and subtracted from those receiving wet food. The formula for estimating the yield of a missing plot (4) may now be used to supply a weight for the missing pig; this is

$$x = \frac{345 \times 4 + 568 \times 3 - 2158}{(4-1)(3-1)} = 154.$$

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[1] See footnote on p. 515.

Substituting this value we obtain the totals 810, 780 and 722 as the total final weights, equalised for litter and feeding, of pigs running two, four, and eight in a pen respectively. Performing the same sequence of operations on the initial weights, and then using the corresponding resultant totals of the initial weights to correct the final weights by means of the regression of final on initial weights, afterwards dividing by four, we obtain estimates of pen effects with the effects of differences of initial weight eliminated.

Table IX. *Computation of effects of numbers in pen.*
Block I. Final weights.

	Litter				
	9	12	19	21	Total
Two in pen	151 (D)	218 (D)	229 (W)	212 (W)	810
Four in pen	194 (W)	190 (W)	191 (D)	205 (D)	780
Eight in pen	x	153* (D)	221* (W)	194* (W)	568
Total	345	561	641	611	2158

* Adjusted for type of feeding (wet or dry).

Table X gives the result of this calculation for the three blocks. The experimental standard error of the mean of four pigs, ± 5·7 lb., is amply large enough to account for the differences observed; clearly therefore neither numbers in pen nor any other factors associated with these sub-blocks produced any appreciable effects.

Table X. *Effects of numbers in pen. Final weights adjusted for differences of initial weight.*

	Block			
	I	II	III	Mean
Two in pen	196·1	173·4	185·7	185·1
Four in pen	191·3	179·0	175·4	181·9
Eight in pen	190·6	179·9	179·2	183·2

In this discussion of the results we have only taken account of the initial and final weights, and total food consumption. There is, however, a large mass of further data available, namely, the intermediate weekly weighings and weekly food consumption. The question remains as to whether there is any additional information to be obtained from this set of data.

That there is little such information is indicated by inspection of the growth curves of the individual pigs. Fig. 1 shows those of litter 21. The growth rate of the pigs receiving green food is remarkably constant, and there is no indication of any differences between the two treatments other than those revealed by the final weights.

A further interesting point revealed by the growth curves is that any temporary disturbance to regular growth tends to correct itself subsequently. Thus a pig that has suffered a check tends to grow more rapidly for a few weeks till it has made up lost ground.

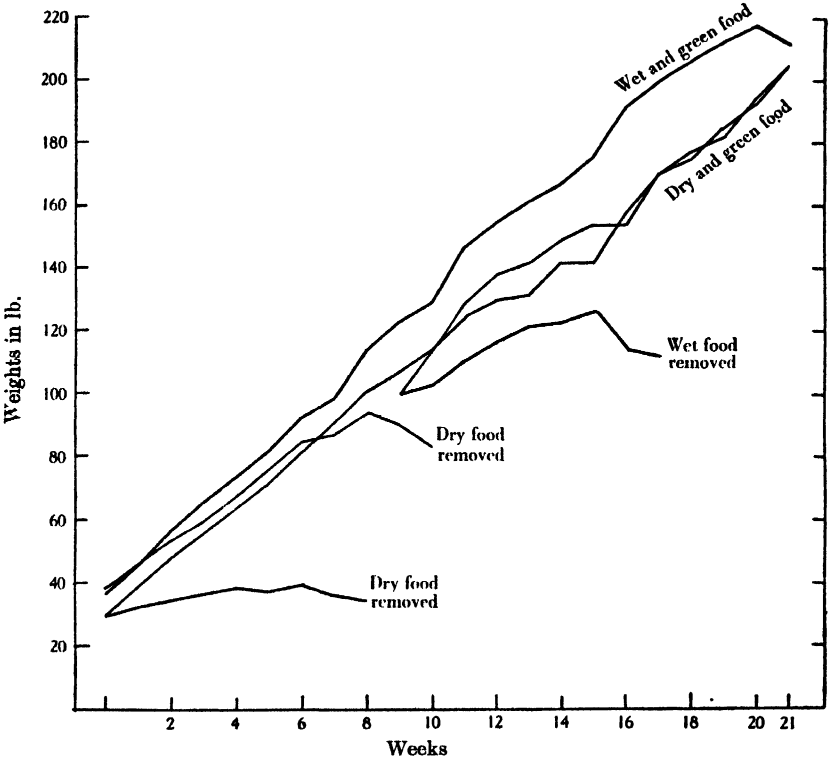

Fig. 1. Growth of pigs in litter 21. The first nine weeks of the pig on wet food and of one of the pigs on dry and green food have been omitted to clarify the diagram.

The intermediate weights are useful as an index of the progress of each pig and they enable definitely defective pigs to be eliminated, but it is doubtful whether any correction for temporary checks, at any rate in *ad lib.* feeding, is justified, especially in view of the apparent later compensation.

All our analyses have been based on the first and last weighings only. A single weighing, however, may be affected by temporary irregularities which will average out when a few consecutive weighings are taken.

It is possible, therefore, that more precise results might be obtained by taking the mean of two or more weighings at the beginning and end of the experiment. For such a procedure to be valid all the pigs would require to be kept for a preliminary period without treatment. This was not done in this experiment, but we may nevertheless determine the error from such meaned results and compare it with that already obtained. This error, taking the means of the two initial and the means of the two final weights, as shown, was found to be 9·9 lb., as compared with 11·3 lb. There thus does appear to be a real, if only small, reduction in error.

The various standard errors obtained in this experiment are summarised in Table XI. Remembering that the amount of information is inversely proportional to the square of the standard error, we see that elimination of initial weight has more than doubled the information from the experiment, and that taking the mean of two initial and two final weights has increased the information by a further 20 per cent. over that obtained with initial weight eliminated.

Table XI. *Standard errors of total live-weight increase (per pig, in lb. and per cent. of increase).*

Without elimination of differences of initial weight	16·1 lb. or 10·8 %
With elimination of differences of initial weight	11·3 lb. or 7·60 %
With elimination of initial weight and food consumption	9·3 lb. or 6·29 %
Means of two initial and two final weights (initial weight eliminated)	9·9 lb. or 7·02 %

COMPARISON WITH DUNLOP'S RESULTS.

Dunlop, in his Cambridge experiments, used a radically different method of experimentation. Individual feeding was used, but instead of *ad lib.* feeding each pig was rationed, the ration of each week depending on the weight of the pig at the beginning of the week. The food allowances were on such a scale that the worst feeders would consume the whole of their ration. Each pig was started on the experimental ration when its weight reached a given value and was then fed on this ration for a given number of weeks.

Using this technique Dunlop obtained remarkably accurate results. He gives the standard error per pig (running for twelve weeks after reaching a weight of 64 lb.) calculated from three experiments (70 pigs, 55 degrees of freedom) as 3·35 lb. This is 3·68 per cent. of the average increase of weight, 91·1 lb. Comparable figures calculated from the Rothamsted experiment give a standard error of 10·5 lb. on an average increase of 88·5 lb. above 64 lb., *i.e.* 11·9 per cent.

The standard errors given by Dunlop are, moreover, overestimates, as he himself admits, for litter effects have not been eliminated, although litter was equalised as far as possible over the different treatments. His errors are computed merely from the deviations from treatment means, ignoring litter and other factors altogether. These errors are consequently considerably biased, since the original design of the experiments consisted of 5 × 5 Graeco-Latin squares involving five litters of five pigs each, in five pens, there being also equalisation for position of feeding pen. The actual design instanced was:

	Pen P					Pen Q					Pen R				
Position in pen	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Litter	4	2	5	1	3	2	5	3	4	1	5	3	1	2	4
Treatment	A	D	B	C	E	B	E	C	D	A	C	A	D	E	B

	Pen S					Pen T				
Position in pen	1	2	3	4	5	1	2	3	4	5
Litter	3	1	4	5	2	1	4	2	3	5
Treatment	D	B	E	A	C	E	C	A	B	D

In such a design a valid estimate of error (8 degrees of freedom) would be obtained on eliminating litters, treatments, pens, and position of feeding pen (4 degrees of freedom each), since these sets of degrees of freedom are all mutually orthogonal. Unfortunately, the litters available did not all contain five suitable pigs, and deficiencies were supplemented by pigs from other litters, so that a partial equalisation of litters was attained, with consequent non-orthogonality of litters, treatments and the other factors. This makes the determination of any error difficult and introduces a very troublesome type of disturbance into the treatment means. The difficulty could only have been avoided by complete redesign, the simplest procedure (though perhaps not the most efficient) being to ignore litters altogether, assigning pigs to their pens and treatments at random.

The trouble has arisen owing to neglect of what we gave as the first requirement of experimental design, namely, that the experiment should be capable of furnishing a valid and unbiased estimate of error. Ignoring pens, about which no particulars are given, it is possible to obtain unbiased estimates of error by direct analysis of the second experiment, and by the rejection of one value in the third experiment and the inclusion of another by means of the missing-plot technique. In the first experiment the fitting of constants must be resorted to. Table XII shows that the unbiased estimates of error are considerably less than those given by Dunlop. In the first and third experiments the litter effects are definitely significant, and in the second experiment are almost significant.

The true values of Dunlop's errors per pig are thus even lower than he claims, and far lower than the errors of the Rothamsted experiment. Dunlop attributes these remarkably low errors to the system of rationing adopted. On the face of it this is possible, for clearly the heavier feeders will grow more quickly, and such differences in growth rate will increase the experimental error. But if differences in food consumption are the main cause of the higher variability in the Rothamsted experiment a considerable reduction should be effected by adjusting the final weights for differences in food consumption by the analysis of covariance. This adjustment was performed on the weights twelve weeks after reaching 64 lb., but the reduction in error, from 10·5 to 9·1 lb. per pig, was quite small. The corresponding figures from Table XI are 11·3 and 9·3 lb. We must therefore postulate that the main cause of the high variability was variation in efficiency of food utilisation. It seems unlikely that had the Rothamsted pigs been rationed almost the whole of this variability would have disappeared.

Table XII. *Errors in Dunlop's experiments.*

				Errors per pig		
Experiment	Duration weeks	Initial weight lb.	Mean increase lb.	Dunlop's estimate lb.	Corrected estimate lb.	Corrected estimate % of increase
Spring 1932	12	64	92·5	4·67*	2·81	3·04
Autumn 1932	17	40	128·0	5·00	4·25	3·32
Spring 1933	12	45	85·4	2·54	1·70	1·99

* Apparently computed wrongly. Should be 4·40.

We are thus forced to the conclusion, on the evidence before us, that part at any rate of the difference in variability must be attributed to the greater homogeneity of material and the better experimental conditions at Cambridge. Whether any of the factors making for higher error at Rothamsted are controllable it is at the moment impossible to say, but it is eloquent testimony to the extreme care with which the Cambridge experiment must have been executed that such low errors were possible by any method[1].'

Further information will shortly be available on the reduction of error likely to be effected by rationing from the rationing experiment now in progress at Rothamsted. In the meantime the greatest caution should be exercised in using the two sets of results as a test of the relative merits of the two methods from the point of view of accuracy.

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[1] See also (1). The series of experiments there described, carried out at McGill University, are comparable with the Rothamsted experiment, except that the effects of litters were not eliminated. Rather higher errors were obtained than at Rothamsted.

Even if the rationed system of experimentation should prove very much the more accurate (which, as we have said, appears unlikely), there remains the vital objection that the experimental conditions are highly artificial. Every departure from ordinary farming conditions makes the experimental conclusions reached of less practical interest and validity, and in many experiments on questions of economic management the whole point of the experiment would be missed with rationed feeding. The difference between wet and dry feeding, for example, would have been completely obscured had the rationed system been adopted.

SUGGESTED IMPROVEMENTS IN EXPERIMENTAL TECHNIQUE.

It is probable that the Rothamsted experiment was too complicated. Leaving aside the failure of the pigs without green food, which was not due to any fault of the experiment, it is clear that the balance of design of this type can be very seriously upset by the failure of a small percentage of the pigs. The interpretation of the results of the present experiment would have been rather troublesome were it not for the fact that neither sex nor numbers in pen had any appreciable effect.

In order to mitigate the disturbance due to the failure of individual pigs, spare pigs on neutral treatment may be carried. This was actually done in the present experiment, but sufficient attention was not given to their selection, and they were none of them from the same litters as the experimental pigs. In view of the significance of litter differences, therefore, results obtained from them were of no value. This has been remedied in the second experiment by carrying one spare pig of each litter for substitution should any pig of that litter fail.

Spare pigs, however, are apt to provide unsatisfactory data. They receive the experimental treatment for only a part of the time, and a pig that is eventually written off as a failure often fails gradually and must be considered defective from the start. The design, therefore, should be kept as simple as possible, in order to enable missing data to be compensated for by the missing-plot technique. Considerable simplification of the Rothamsted design could have been made if sex had been ignored and investigations of the effects of variation of numbers in pen omitted. Litters of four might then have been used, the whole of each litter being run in one pen (one pig of each litter receiving each treatment). Litter and pen effects would then be confounded with consequent simplification of the analysis. Similarly in a 3 × 2 experiment litters of six pigs could be utilised, and in a 2 × 2 × 2 experiment litters and pens of four with the second-order interaction confounded.

Another possibility which has not so far been considered is to use a group of pigs instead of a single pig as an experimental unit. With groups of four, for example, each unit could be run in a separate pen, with the pens arranged in randomised blocks. The experiment would have to be a large one in order to provide a sufficient number of degrees of freedom for experimental error, for the analysis must be based on the totals of each unit and not on the individual pigs. On the other hand, in view of the small pen effects actually observed, the efficiency of the experiment measured on the basis of a single pig will probably be about the same as with individual feeding, at least with *ad lib.* feeding where competition at the feeding trough does not come into play. The great advantage of this method of experimentation is that the labour of feeding is very considerably reduced, and less elaborate pens are required. Where plenty of material is available it may be the most efficient method. The radical difference between this and the old group-feeding method is that in the old method there was entirely inadequate or no replication of the groups. With adequate replication and proper randomisation the conclusions can be made as statistically valid as those reached by individual feeding.

SUMMARY.

1. The conditions which must be fulfilled in the design of an animal husbandry experiment if the results are to be statistically valid are summarised, together with possible methods of improving the efficiency by suitable design.

2. The results of a pig-feeding experiment conducted at Rothamsted are discussed. The experiment showed that green food was essential to young pigs under the conditions of the experiment, that pigs fed on a wet mash grew at a faster rate than pigs fed on dry meal, the difference being due to the greater quantity of food consumed by the former, and that the effects of numbers in a pen (giving equal floor space per pig) were negligible in spite of the greater possibilities of exercise in the larger pens.

3. The various standard errors of the experiment are evaluated and compared with the results of Dunlop's experiments at Cambridge. It is pointed out that the considerably lower errors of the Cambridge experi-

ment, attributed by Dunlop to his method of rationed feeding, may be due to other causes.

4. Possible modifications of the present type of design are discussed.

In conclusion I should like to mention that this paper was originally planned as a joint one with the late Mr H. G. Miller, the Farm Director at Rothamsted, who was in charge throughout of the practical execution of the experiment. His illness and untimely death, however, prevented him from taking any part in it.

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SOME EFFECTS OF CLIPPING THE TOPS UPON THE ROOT DEVELOPMENT OF LUCERNE (*MEDICAGO SATIVA* L.).

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(With One Text-figure.)

I. INTRODUCTION.

THE problem of cutting lucerne in the seedling year is one that has been much discussed. As long ago as the eighteenth century B[artholomew] Rocque (1), of London, wrote as follows:

"In Languedoc they sow no Corn with it: And, when the Lucern is six or seven Inches high, they mow it; by which all the Seeds of annual Weeds are cut off and killed.

"By my own Experience, I find they are in the wrong; for it bleeds it, so that the Plants make but little Progress..."

The second paragraph occurs in the second edition (1765) only, suggesting that the author had had several years' experience of the harmful effect of cutting lucerne too early. Rocque's opinion, however, was far from meeting with universal acceptance. Indeed, the view that early cutting encouraged the vitality of young lucerne persisted in America until the beginning of the present century; for some typical opinions see McKee (2) and Graber *et al.* (3) At the present day, however, it is widely recognised among American agronomists that excessive cutting in the seedling year is harmful.

Sundelin and Franck (4) concluded from experiments in Sweden also, that lucerne should not be cut during the year of sowing. They sowed lucerne in mid-June in successive years and examined the effects of not cutting in the year of sowing and of cutting after about 61, 83 and 100 days, recording the yield (of two cuts) in following years. Marked depressions in yield followed after the late cuts, the extent of the effects varying with season. Early cuttings in the year of sowing were performed in August, and so enabled the plants to recover before winter. From the results of Sundelin and Franck it appears that the effects of cutting very young plants were largely offset when the plants were allowed to recuperate before the onset of winter. In 1922 late autumn cutting of newly-sown lucerne prejudiced the yield for three years afterwards. In the case of lucerne sown in 1923, the cut, whenever taken in that year, severely depressed the yields of 1924 and 1925. Sundelin and Franck refer, however, to June sown lucerne, upon which the effect of cutting the young plant may be more harmful than upon lucerne sown in spring as seems desirable in this country.

The results of cutting are somewhat complex and it is important to distinguish its influence upon the plant's food reserves from secondary effects, as upon weed infestation on the one hand and on the other hand upon possible reduction in autumn growth and in the consequent winter covering. This distinction is of practical importance, since the magnitude of these various effects is much influenced by the time as well as the frequency of cutting. The present work deals with the influence of clipping upon the plant's food reserves.

In the case of a nodule-bearing legume, cutting might affect the food reserves in two ways, either by its direct influence upon the materials translocated to or from the roots, or, indirectly by influencing nitrogen fixation in the nodules. These two effects can be distinguished by comparing the mass and composition of roots and tops in clipped and unclipped plants on the one hand and on the other by estimating the effect of clipping[1] upon the total nitrogen fixed. The literature records very few studies of the effect of cutting lucerne upon its root development, although, as pointed out by Graber (5), its clear-cut responses to cutting treatments make this plant valuable as a medium for initial investigations on root reserves. A review has been made by Nicol (12).

Graber wrote a largely theoretical paper on the growth of lucerne with various cutting treatments. His tentative conclusions appear sound in the light of later work (3, 6, 7, 8). Late or excessive cutting, according to Graber, leads to (1) smaller root reserves, (2) lessened absorptive capacity of the roots, (3) increased winter killing, (4) increased invasion by weeds owing to encroachment by them upon spots left bare by winter killing. Definite figures relative to the effect of clipping upon thickness of stand, as well as upon the diameter of roots, of lucerne plants were given by McKee (2); some of his results are summarised in Table I. Other measurements of root diameters of clipped and unclipped lucerne, performed by later workers (9, 10), have borne out the conclusions

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[1] The term "clipping" is here used to designate the equivalent in pot culture work to cutting or mowing in the field.

Table I. *Effect of clipping in year of sowing upon number of lucerne plants and diameter of lucerne roots. Data of McKee* (2).

	Measurements made in	Treatment	Total number of plants	Average diameter of roots mm.
Sown in rows	1912	Clipped	116	7·49
	1912	Not clipped	104	10·48
	1913	Clipped	152	10·98
	1913	Not clipped	218	12·90
Sown broadcast	1913	Clipped	1619	6·56
	1913	Not clipped	1829	6·91
	1914	Clipped	977	6·34
	1914	Not clipped	1013	6·93

suggested by McKee's figures. A review of several papers on cutting, root development, and winter killing has been given by Kiesselbach and Anderson (11). A small reduction in mean root diameter probably reflects a considerable diminution in total mass of root but, since the correlation between these two measurements is imperfectly known[1] and probably variable, the conclusions to be drawn from root diameters are at best somewhat uncertain. The authors have been unable to find any published data from which it is possible to determine whether cutting affects the quantity of nitrogen fixed or merely alters the distribution of nitrogenous and other food materials between the roots and tops. They therefore undertook in 1933 an investigation of the effects of cutting young lucerne once and twice, with a view to obtaining a measure of the root development and nitrogen content of cut and uncut lucerne, grown in sand culture in glazed pots.

II. PLAN OF EXPERIMENT.

The experiment was carried out in an unheated greenhouse. Thirty-six large glazed pots each holding about 20 kg. of clean river sand and watered with nitrogen-free food solution were sown with lucerne and Italian rye-grass on April 20th. Four harvests[2] were made at intervals of about three weeks, namely on June 14th (set A), July 6th (set B), July 27th (set C) and August 24th (set D). Up to July 5th all pots received the same treatment, but on that date the lucerne in ten of the pots was clipped. The crop in five of these pots was harvested on

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[1] Nelson (10) concluded from measurements of over 200 lucerne plants that the green weight of the roots was closely correlated with "the squares of the root diameters near the crown."

[2] Throughout this paper the terms "harvest" and "harvesting" refer to the turning out of the roots and sand from the pots.

July 27th together with that from six pots in which the lucerne had not been clipped, the eleven pots comprising series C. The remaining five pots of clipped lucerne were again clipped on July 26th and harvested together with six pots of unclipped lucerne on August 24th (series D). Table II shows the dates of clipping and of harvesting (*i.e.* washing the roots) for each set of pots.

Table II.

	Harvest set					
	A	B	C		D	
Date of harvest	June 14	July 6	July 27		August 24	
Dates of clipping	Unclipped	Unclipped	Unclipped	July 5th	Unclipped	July 5th July 26th
Number of replicate pots	8	6	6	5	6	5

III. TECHNIQUE.

On April 20th, 1933, about twenty-five seeds of Grimm lucerne, "inoculated" with an active nodule-forming strain of lucerne nodule bacteria, were sown in each pot. Each seed was placed at the bottom of a small depression made in moist sand and later covered with the surrounding sand. On the day prior to sowing every pot received 500 ml. of food solution (0·5 gm. each of K_2HPO_4, KH_2PO_4, NaCl, $MgSO_4.7H_2O$, and $CaSO_4$, made up to 500 ml. with rain water with the subsequent addition of 0·04 gm. "anhydrous" ferric chloride). Further quantities, uniform for all pots at one time, of food solution and of rain water were added as thought necessary throughout the period of the experiment. No nitrogenous manure was added at any stage.

In addition to the lucerne seed, about twenty-five seeds of Italian rye-grass were sown in each pot, and a further four pots were sown with the rye-grass alone. The grass, however, made very little growth, and this was scarcely affected by the clipping treatment. Randomisation was adopted throughout, as regards the position in the greenhouse of the various treatments (clippings) and of the pots within each treatment, and as regards the taking of pots for harvesting. Pots were harvested after allowing them to remain unwatered for a few days so that they dried out; then the contents were emptied on to a coarse sieve and the plants (lucerne and grass) separated as completely as possible. Counts of nodules in each pot were made and from 50 to over 200 nodules per pot were measured for length. In all but the first harvest of lucerne, roots and tops were separately dried and weighed and analysed for nitrogen. The first harvest of lucerne, and the grass throughout, were weighed and analysed for nitrogen as whole plants. Clippings were made with a pair of scissors using eye judgment only, so as to leave about 10 cm. of stem. The clippings from the lucerne were dried, weighed and analysed for nitrogen apart from the rest of the lucerne plants. Those pots in which the lucerne had previously been cut were harvested similarly to the other pots. Those four pots containing grass only were harvested at the end of the experiment (August 24th). All dry weights of lucerne roots and tops, of lucerne clippings, and of grass, were taken in the air-dry state after exposure in a drying room. Analyses were performed by the Chemistry Department of this Station upon the air-dried samples after they had been ground to a fine meal. Dry weights and analyses were obtained separately from each pot, but only the means of the replicates are presented in the tables following. The agreement between replicate pots was good, especially so in the case of the clippings from standing lucerne.

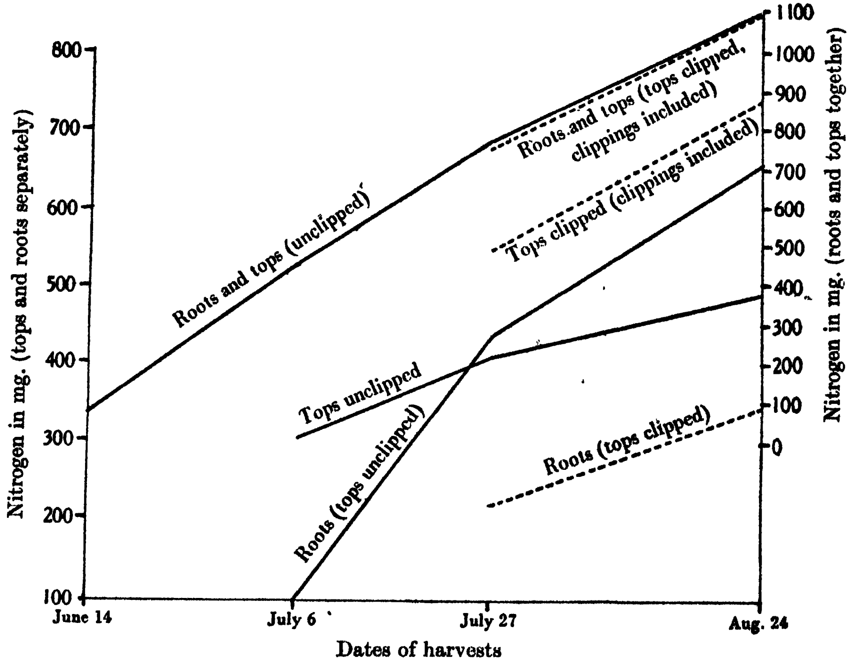

Fig. 1. Influence of clipping the tops of lucerne upon the nitrogen distribution in the plant.

IV. Results.

The results of the experiment are summarised in Tables III and IV and in Fig. 1, where the data quoted represent means of the replicate pots the number of which are given in Table II. Standard errors of these means are italicised in Table III for sets C and D.

Table III. *Nodule numbers, dry weights and total nitrogen in clipped and unclipped lucerne (sown April 20th).*

Set	A	B	C			D		
Date of harvest ...	June 14th	July 6th	July 27th			August 24th		
Dates of clipping ...	Unclipped	Unclipped	Unclipped	Clipped July 5	Difference	Unclipped	Clipped July 5 and July 26	Difference
Number of nodules per pot	294	932	1222	1147	−75	898	1000	+102
Mean nodule length, mm.	2·26	1·65	2·46	2·36	−0·1	2·88	2·73	−0·15
Dry matter of lucerne in gm.:								
Tops	—	10·37	17·74 *±0·33*	18·49* *±0·79*	+0·75	20·42 *±0·50*	24·47† *±0·90*	+4·05
Roots	—	5·82	16·50 *±0·46*	10·33 *±1·94*	−6·17	21·12 *±0·91*	16·04 *±1·51*	−8·08
Total	2·29	16·19	34·24 *±0·62*	28·82* *±2·09*	−5·42	44·54 *±1·05*	40·51† *±2·39*	−4·03
Nitrogen in lucerne in mg.:								
Tops	—	301·1	419·1 *±15·81*	548·3* *±16·45*	+129·2	489·8 *±23·53*	741·9† *±31·02*	+252·1
Roots	—	152·0	380·3 *±10·33*	222·2 *±30·35*	−158·1	606·4 *±22·97*	343·3 *±122·7*	−263·1
Total	71·5	453·1	799·4 *±21·54*	770·5* *±43·90*	−28·9	1096·2 *±28·34*	1085·2† *±68·51*	− 11·0

* Including clipping: dry weight 6·87 gm., N 228·1 mg.

† Including first clipping: dry weight 6·98 gm., N 233·2 mg.; second clipping: dry weight 6·84 gm., N 243·2 mg.

Table IV. *Percentages of nitrogen in clipped and unclipped lucerne.*

Set	A	B	C		D	
Date of harvest	June 14th	July 6th	July 27th		August 24th	
Clipping	Unclipped	Unclipped	Unclipped	Clipped once	Unclipped	Clipped twice
In:						
Roots	—	2·62	2·31	2·15	2·52	2·12
Standing tops, at date of harvest	—	2·91	2·36	2·77	2·48	2·41
First clipping, July 5th	—	—	—	3·36	—	3·35
Second clipping, July 26th	—	—	—	—	—	3·55
Mean for whole plant *plus* clippings, if any	3·11	2·80	2·34	2·67	2·46	2·68

The unclipped lucerne showed a steady increase in dry weight and nitrogen content both as regards tops and roots during the growing period.

The young tops harvested in June and the clippings taken in July were richer in nitrogen than were the more stemmy attached tops harvested in July and August. The total nitrogen content of the plants (roots and tops including clippings) was not significantly affected by clipping. This did not therefore affect the activity of the nodules. It was also without significant effect upon their numbers and mean size. There was, however, a striking translocation of nitrogen from roots to tops in the clipped plants. In series C, the single clipping increased the nitrogen content of the tops, *plus* clippings, by 129·2 mg., a gain of 30·8 per cent. over the unclipped series, but it reduced the nitrogen in the roots by 158·1 mg., a loss of 41·6 per cent. In series D, the two clippings raised the nitrogen content of the tops by 252·1 mg. (51·5 per cent.), but reduced that of the roots by 263·1 mg. (43·4 per cent.).

Clipping produced a comparatively slight increase in the dry weight of the tops, *plus* clippings, over that of the unclipped tops, but it resulted in so considerable a reduction in the dry matter of the roots that the total dry weight of the whole plant, roots, standing tops and clippings, was appreciably reduced in series C and less so in series D. Since this reduction in total dry matter did not involve the nitrogen it must have concerned the carbon and consequently have represented a lessened photosynthesis or else a more rapid oxidation of carbon by the plant or by the bacteria in the nodules.

V. SUMMARY AND ABSTRACT.

1. Inoculated lucerne was grown in pots of sand and watered with nitrogen-free food solution. In some of the pots the lucerne was clipped once, in some twice and in some it was left unclipped. Pots were harvested on four dates at intervals of about three weeks. Counts and measurements of nodules were made and dry weights and nitrogen contents of tops and roots were obtained.

2. Clipping did not significantly alter the nodule numbers, their mean size, or the total nitrogen contents of the plants, *i.e.* in tops, including clippings, *plus* roots.

3. Clipping, however, resulted in a decrease in the nitrogen content of the roots of about 40 per cent. as compared with unclipped plants. This nitrogen was transferred to the tops where it was removed in the clippings.

4. In clipped plants the total yield of the tops, including clippings, was slightly increased but that of the roots was greatly depressed. This resulted in a reduction in total dry weight of the whole plants.

VI. ACKNOWLEDGMENT.

The authors wish to record their thanks to Miss Sheila Arnold for her assistance in the greenhouse and in making weighings in the laboratory.

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FURTHER EVIDENCE UPON THE NITROGEN UPTAKE OF GRASS GROWN WITH LUCERNE.

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(With One Text-figure.)

THE practice of growing mixed crops of legumes and non-legumes is widespread. There is reason to believe that clovers growing with grasses in a pasture do not merely act as a direct source of protein for animals, but also contribute to the nitrogenous intake of the grasses. The earliest reference to possible benefit derived by a non-legume from a legume growing beside it appears to have been made by Leather (1897), though Sinclair (as quoted by Wilson (1848) in a reference that has not been traced by the authors) had noted that a mixture of many grasses grew better than only one or two species. Sinclair (1816), like eighteenth-century writers, used the term *grass* in a wide sense to include leguminous pasture plants. The first experimental demonstration of a non-leguminous plant grown with only that nitrogen supplied by a leguminous plant was made by J. G. Lipman (1910). A review of the available literature upon the excretion of nitrogenous compounds by legumes has been made by one of us (Nicol, 1934), and it will therefore suffice here to state that the reality of a gain of nitrogen by a non-legume when grown in association with a legume seems to have been established, though the mechanism is still obscure.

In 1931 the authors carried out an experiment wherein lucerne and Italian rye-grass were grown together in pots in sand. Sodium nitrate was used at three low levels, namely 0·33, 1·0 and 3 gm. per 20 kg. of sand, one dose being added to each pot at the time of sowing the seed. The results of the growth of grass, as shown in Fig. 1, indicated that considerably more nitrogen than had been supplied was found in the grass from those pots which had received the two smallest doses (*AA* and *BB*) of nitrate. The recovery varied from two to nearly six times the initial dose of nitrogen, even on the assumption that none of the nitrate had been taken up by the lucerne.

The results for the grass in 1931 have already been given in detail (Thornton and Nicol, 1934 *a*) both as regards dry weight and nitrogen content, but the figures for nitrogen content are repeated in graphical form in Fig. 1 for the sake of comparison with the 1933 results.

In 1933 similar mixtures of lucerne and rye-grass were grown, but to these no nitrogenous manure was supplied. Whereas in the 1931 experiment no grass was grown by itself, in 1933 four pots were sown with grass only. In respect of greenhouse technique the experiments were similar (for details see Thornton and Nicol (1934 *a*, 1934 *b*). In both years harvests were made at approximately regular intervals throughout the growing season, except that the grass grown by itself was not harvested until the time of making the last harvest of the mixture of lucerne and grass. Harvesting implied the turning out of the pots and, usually, separation of roots and tops of each species, though in 1933 the grass roots and tops were analysed together.

The 1933 experiment also provided information upon the effects of clipping or cutting the lucerne tops. The effects of clipping upon the lucerne component of the mixture have been discussed elsewhere (Thornton and Nicol, 1934 *b*). This paper is concerned only with the effects of lucerne, clipped (in 1933) and unclipped (in 1931 and 1933), upon the growth of the grass.

Results of the harvesting of grass grown alone and with clipped and unclipped lucerne are presented in Table I. Each determination in the table is an average obtained from the number of parallel pots shown.

Table I. *Growth of grass (tops and roots), sown with and without lucerne, on April 20th,* 1933 (*Rothamsted*).

Date of harvest, 1933 … …	June 14th	July 6th	July 27th		August 24th		August 24th
With lucerne …	Un-clipped	Un-clipped	Un-clipped	Clipped	Un-clipped	Clipped	Grown alone
Number of parallels	*8*	*6*	*6*	*5*	*6*	*5*	*4*
Dry matter, gm.	0·38	0·86	1·2	1·4	4·5	6·9	5·15
Nitrogen, %*	0·84	0·93	0·86	0·92	0·86	0·65	0·33
Total nitrogen, mg.	3·1 ±0·44	7·7 ±0·60	10·1 ±0·74	12·7 ±1·28	37·1 ±5·94	40·2 ±3·50	16·5 ±0·26

* Unweighted means.

The grass at the first harvest contained only 3·1 mg. of nitrogen. By August 24th the grass grown alone contained 16·5 mg., the difference being presumably derived either from impurities in the sand or from nitrogen fixed by free-living bacteria. The presence of lucerne further increased the nitrogen content of the grass to 37 and 40 mg. by August

24th, that is in about 4 months. It appears probable from its rate of nitrogen increase, that the grass grown with lucerne did not contain appreciably more nitrogen than that grown alone until after July 27th, or, in other words, that the uptake by grass of nitrogen from lucerne in the absence of added nitrogen began after about 3 months from sowing.

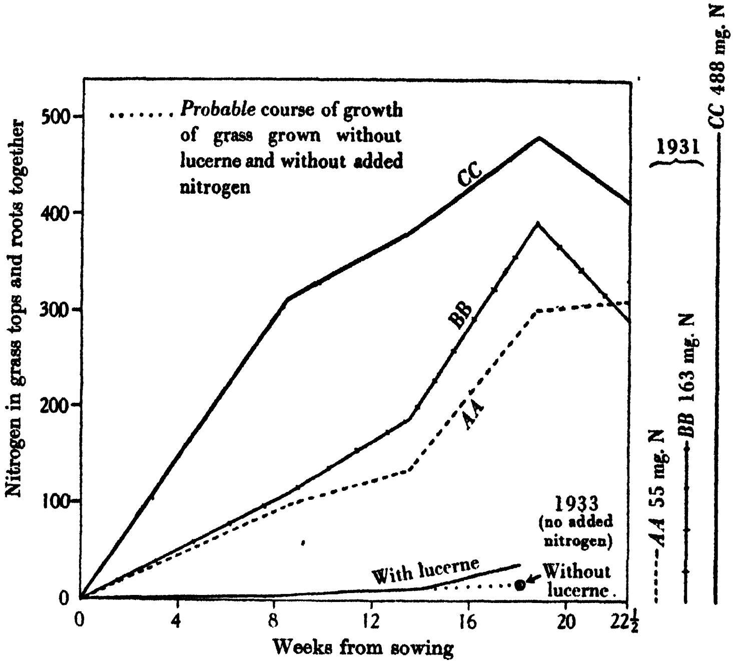

Fig. 1. Milligrams of nitrogen in grass (roots and tops together). The three uppermost curves indicate the course of nitrogen uptake in 1931 of grass grown in presence of lucerne; three levels of nitrogen as sodium nitrate were added in one dose at the time of sowing. The doses of nitrogen are represented to the same vertical scale and with the same kind of lines at the right of the figure. The dot represents the nitrogen content of grass grown in 1933 in absence of both lucerne and added nitrogen, while the thin line near the bottom shows the nitrogen content of grass grown with lucerne in absence of added nitrogen. For this curve were taken the means of the results from grass grown with clipped and unclipped lucerne. Each point represents the mean of results of from three to eight parallel pots in which the plants were grown in sand.

There was probably no significant effect upon grass of clipping the lucerne. In this experiment, therefore, where no nitrogenous manure was given, the uptake of nitrogen by the grass from the lucerne appears to have begun later than was the case in the 1931 experiment where small doses of nitrate were applied. It seems likely that such small doses of nitrate, by encouraging the early root development of the grass, increased its capacity for absorbing nitrogen compounds from the lucerne.

The authors have made no attempt to trace out the course of the supposed transfer of nitrogen from legume to non-legume. Virtanen (1933 *a*, *b*) has recorded finding in pure sand, in which inoculated legumes were grown, amounts of combined nitrogen of the same order as that existing in the plants themselves. Wilson, of Madison, Wisconsin (1934), stated that he has tried to repeat the technique of Virtanen and his co-workers, so far without being able to confirm their findings regarding the excretion of nitrogenous compounds by leguminous plants.

SUMMARY AND ABSTRACT.

1. Italian rye-grass grown in the presence of lucerne in sand with no added nitrogen contained, after 18 weeks' growth, some 2¼ times as much nitrogen as did grass of the same age similarly grown but in the absence of lucerne.

2. In another experiment, where lucerne and grass were grown together in sand:

(*a*) Where 0·33 gm. of sodium nitrate was added per pot, the grass after only 13½ weeks' growth contained 2½ times, and after 18 weeks' 5½ times, as much nitrogen as was supplied as nitrate.

(*b*) Where 1·0 gm. of nitrate was added, the grass after 13½ weeks contained slightly more nitrogen than was added as nitrate, and after 18 weeks it contained 2¼ times as much.

(*c*) Where 3·0 gm. of nitrate were supplied, there was slightly less than a quantitative recovery in the grass of the nitrate nitrogen supplied.

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SCIENTIFIC RESEARCH IN SOIL DRAINAGE.

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(With Two Text-figures.)

The science of land amelioration, or "Kulturtechnik" as it is called in Germany, where it has been chiefly developed, is concerned with the scientific principles underlying the improvement of agricultural land by such means as artificial soil drainage, irrigation, river regulation and land reclamation. Since the War it has been attracting increasing attention throughout the Continent, and it now ranks as one of the most important branches of soil science. In England land amelioration has, for political and economic reasons, been very much neglected during recent years, and in consequence there has been little opportunity for scientific research on problems relating to it. The difficulty of studying these problems is greatly increased by the fact that some of the most important literature is either inaccessible or is only available with difficulty in Great Britain. It is hoped that the present résumé will to some extent fill the gap as far as one particular branch—that of artificial drainage in mineral soils—is concerned. Discussion of the drainage of peat soils has been omitted, since this presents rather different problems, and can only be adequately considered in relation to the reclamation of such soils as a whole. Mole drainage and the various combined mole-tile systems have also been left out of consideration to a great extent, since, in spite of their importance, very little scientific research has been done on them. Except where otherwise stated, the present account is confined to tile drainage.

Drainage research is faced with two different but interrelated problems: the practical one of determining the optimum design for a drainage system on any given piece of land, and the more purely scientific one of determining how the system functions, and what effect it has on the soil and on the crop.

THE OPTIMUM DESIGN FOR A DRAINAGE SYSTEM.

The points which have to be considered in designing a system are: (*a*) the arrangement of the drains with respect to each other and to the topography of the land; (*b*) the depth and distance apart of the minors;

(*c*) the size and quality of the tiles; (*d*) the method of laying the tiles and of refilling the trench, including, if necessary, special precautions to prevent blockage of the drain; (*e*) the construction and protection of the outfall; (*f*) the provision of inspection pits, settling chambers, etc., where necessary. Scientific research has concentrated chiefly on (*b*), which is undoubtedly the one on which information is most urgently required, and has left the others more in the hands of the practical drainer.

THE OPTIMUM DRAIN DEPTH AND DISTANCE.

The term "optimum drain distance" has significance only from the economic point of view. It is the distance apart of the minors which gives the best return on the money or labour expended in construction, but not necessarily the one which leads to the greatest improvement in the land. From the latter point of view there is no reason to suppose that medium or heavy soils could ever be overdrained, in the sense that the effectiveness of the system could be diminished by laying the drains too close together. At all events the cost of such a system would be prohibitive. In light soils however the possibility of overdraining is a more real one. The optimum drain depth can be considered from the point of view either of maximum effectiveness or of best economic return. A system will be ineffective if it is laid either too shallow or too deep, and there should thus be some intermediate depth at which it is most effective. Since the cost of construction does not vary much with slight changes in depth, this may coincide approximately with the optimum economic depth.

The effectiveness of a drainage system with a given depth and disance will depend on: (*a*) the nature of the soil, including mechanical composition, structure, percentage of calcium carbonate and organic matter; (*b*) the crop and, more generally, the type of farming practised, *e.g.* grassland or arable, extensive or intensive; (*c*) the topography of the land; (*d*) the weather; (*e*) the cause of the unfavourable moisture conditions, *e.g.* the impermeability of the soil, seepage from higher levels, or the lack of an adequate drainage outlet for the groundwater. (*b*) to (*e*) have received comparatively little attention compared with (*a*). It will be seen that two of the factors which determine the optimum dimensions of a system—namely the agricultural price level and the weather throughout the life of the system—are unpredictable. In practice the life of the system also can only be estimated approximately. There is thus an element of inherent uncertainty which prevents the optimum design from being determined beyond a certain degree of accuracy.

The most direct method of determining the optimum drain depth and separation under given conditions is to lay out an experimental field in which different plots are drained in different ways. The earliest field of this kind which is still in existence was laid out by Fauser (1910 *b*) in 1909 on a heavy soil at Ellwangen, Wurtemberg. It consisted of nine differently drained plots and one undrained, with no replication. Results from it have only recently been published (Fauser, 1933), but it appears that all the systems tried out were inadequate, and hence that no positive conclusions could be drawn as to the optimum design on this land.

During the past ten years a number of experimental drainage fields have been laid out in Czecho-Slovakia, which has always been one of the most progressive countries in Europe where soil improvement is concerned. Details of these, and the experimental results, are published in the annual reports on "Kulturtechnik" issued by the Czecho-Slovakian Ministry of Agriculture from 1924 onwards[1]. Most of the relevant information is given only in Czech, but short German and French summaries are added. There is practically no replication in any of these fields, so that the information is of a qualitative rather than an exact quantitative kind, but it is sufficient to justify some important changes which are to be introduced into Czecho-Slovakian drainage practice. These are discussed by Janota (1932), who considers that the most definite result which has emerged is that in wet seasons shallow drainage (0·8–1·0 m.) is more efficient in heavy soils than deep drainage. This contradicts the older continental view that for a given distance apart the deeper drainage should be the more effective. In dry seasons on the other hand, the deeper and more widely spaced systems were sometimes the most effective, and they generally showed an increased yield over the undrained plots even when the crops had suffered from drought. This variation in the relative effectiveness of different systems from year to year greatly increases the difficulty of deciding which will give the best total economic return over its whole life. Table I shows the results from the largest of the experimental fields for two years. 1929 was unusually dry and 1930 fairly normal.

The order of effectiveness of the different drain distances in the dry year is almost the exact opposite to that in the normal one. A similar tendency can be observed with the different depths. Corresponding data for an abnormally wet year have not been published for this field.

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[1] *Zprávy výzk. úst. zeměd. R.Č.S.* (1924–5), No. 21, (1926), No. 29. *Sborník výzk. úst. zeměd. R.Č.S.* (1928–31), Nos. 55, 64, 72, 92.

Table I. *Yields of experimental plots at Záhati (Moravia).*

Drain depth m.	Drain distance, m.					
	6	8	10	12	14	Average
	1929. Sugar beet. Weight of roots in dz./ha.*					
0·8	409	384	411	434	451	418
1·1	387	423	450	459	435	431
1·25	420	423	436	439	438	431
1·4	426	418	457	457	447	441
Average	411	412	439	447	443	
	Undrained plot: 408.					
	1930. Barley. Weight of grain in dz./ha.					
0·8	31·9	30·4	34·0	34·8	33·3	32·9
0·95	43·4	42·4	42·5	33·6	31·0	38·6
1·1	39·0	39·2	40·8	41·2	40·1	40·1
1·25	42·2	42·6	34·9	36·1	29·8	37·1
1·4	41·3	41·0	42·5	37·2	39·2	40·2
Average	39·6	39·1	38·9	36·6	34·7	
	Undrained plot: 35·9.					

* 1 dz./ha. = 0·80 cwt./acre.

Preliminary results from an experimental field in Kvorning, Denmark, have been published by Thøgersen (1930). Six different combinations of drain depth and distance were tried, together with an undrained plot, each with twofold replication. It was found that all the drained plots gave a substantial increase in yield over the undrained, but no clearly significant differences between the various drainage systems could be established. The average increase in yield of the drained over the undrained plots during the first three years was:

Year	Crop	Average increase in yield (dz./ha.)
1927	Oats	Grain 3·2 Straw 11·6
1928	Turnips	126
1929	Barley	Grain 7·4 Straw 9·5

The rainfall was exceptionally low during 1929, and was also below the average in 1928.

An experimental field was also laid down at Friedrichstein, East Prussia, by Rothe (1933) in 1929. The results so far published have not shown any significant differences between the drained and undrained land, or between the different drain separations. It seems likely, therefore, that the field was not really in need of drainage. Other drainage fields have recently been laid out in Finland (Keso, 1930), Russia (Rozov, 1932) and Bavaria (Weigmann, 1933).

The design and management of experimental fields have been fully discussed by Fauser (1932) and by Hallakorpi (1932). The main difficulty as a rule is to find suitable land. Each single plot must be comparatively large, and a large area is therefore required if several different systems are to be tried out with adequate replication. The whole field must be homogeneous, with a fairly uniform slope, and must be free from disturbing influences such as seepage from higher levels. It must also be typical of sufficiently large areas which need drainage in the country as a whole, in order that the conclusions can be applied practically. Systematic experimental fields should therefore be confined to the more important soil types, and would not be justifiable on mixed or unusual soils. With this limitation they should provide valuable information not only on the practical question of economic returns but also on the effect of drainage on soil properties, soil water relations, and plant growth.

On other soils a simpler way of estimating the optimum drain depth and distance is required. Schroeder (1928) has suggested a method by which this could be done. He recommends that drainage systems should normally be carried out in two stages instead of one. In the first year only the mains and a few selected minors are laid. The positions of the minors are chosen partly to be typical of the field as a whole, and partly to intercept springs or ground-water currents if there are any indications of these. While the trenches are being dug the soil profile throughout the field can be carefully studied and the information obtained can be applied later in designing the rest of the system. During the first year the effect of the "skeleton" system on the soil moisture conditions and crop yields at various distances from each drain is observed, and from this the optimum distance apart of the minors is deduced. The system is then completed in the second year. In some soils where systematic drainage would normally have been applied, it may be found that the excessive soil moisture was simply due to seepage along a few permeable veins and that the skeleton system was sufficient by itself to remedy the trouble.

The chief objection to adopting this as a normal procedure is that the behaviour of a drain during the first year of its life is not always a reliable indication of its subsequent behaviour. In heavy soils, for instance, a system usually does not attain its maximum efficiency until 2 or 3 years after construction. The effect of drainage also depends very much on the weather, and if this happens to be at all abnormal during the first year the conclusions drawn may be inapplicable to more normal conditions. Whether these considerations are sufficient ground for rejecting the slight extra trouble and expense involved in Schroeder's method must be decided according to particular circumstances. In any case, skeleton systems of this sort which were left uncompleted for a number of years and on which accurate observations were made, should be cheap and useful alternatives to systematic experimental fields, on soils where the latter were impracticable.

A somewhat similar method has been adopted by Rothe (1929) and is fully described by Bonacker (1928). Previously drained fields were selected in which the drain distance was obviously too wide—shown by the fact that the crops were growing much more vigorously near the drains than half-way between them. At harvest time several strips were marked out, running perpendicular to the drain direction from one lateral to the next. Each strip was divided into a number of small plots and the yield of each plot determined. The variation of yield with distance from the drain was thus found, and the most economic drain distance deduced. The hygroscopicity and mechanical composition of the soil in each strip were also determined and a certain correlation was found between each of these properties and the optimum drain distance deduced as above. On the strength of this correlation Rothe has put forward formulae relating drain distance in metres (E) to hygroscopicity (W_h) and the percentage of particles less than 0·02 mm. diameter (W_e) respectively:

$$E = \frac{78}{W_h}, \quad E = \frac{425}{W_e}.$$

These apply for a depth of 1 m. in arable land for the economic conditions prevailing at the time.

The method appears in principle to be a valuable one, but the actual formulae have only a limited significance, since (*a*) the economic assumptions on which the optimum distance was deduced are open to criticism, and (*b*) the formulae were based on measurements on only eleven different strips situated in two rather similar fields, and of these strips three had to be rejected since no optimum distance could be deduced from them.

The methods so far discussed have been concerned with the direct determination of the most effective drainage system under given conditions. Most research has, however, approached the subject from a different point of view. It has started on the assumptions (*a*) that the optimum drain distance is a simple function of the "heaviness" of the soil or of some related property, and (*b*) that on any given soil type the optimum distance is already known approximately by practical experience. The problem is thus reduced to one of finding a scientific test by which the soil can be classified, on the basis of heaviness, into its appropriate type. It can then be given the drainage system which is considered to be the most suitable for that type. A number of tables have been drawn up by experts in different parts of Europe, in which the most suitable depth and distance are given for soils such as clay, heavy medium and light loams, and sandy soils. The more important of these are given by Kopecky (1901), Breitenbach (1911) and Friedrich (1921).

The value of research along these lines will depend on two considerations: (*a*) Are the practical scales sufficiently reliable for the scientist to work on? (*b*) Is the subjective judgment of soil type sufficiently unreliable to justify its replacement by an objective test? These questions are to some extent interdependent, since the scales in general use were drawn up in the first place on the strength of personal experience without the help of scientific measurements. If personal experience is really unreliable there will be no object in basing scientific tests on it, and if it is already sufficiently reliable the tests are unnecessary. In practice there is no doubt that an objective test will be a great help to a less experienced designer and may sometimes give useful information even to the most experienced. On the other hand it is clear from the considerations already mentioned that there is no point in developing these tests beyond a certain degree of accuracy so long as they continue to be ultimately based on purely personal experience. Exaggerated claims have sometimes been made on their behalf, which need to be treated with scepticism[1].

The most widely used scientific method of soil classification for drainage is Kopecky's elutriation method of mechanical analysis. This was first introduced by Kopecky (1901) into Bohemia, and is now used for the purpose in Czecho-Slovakia, Switzerland, parts of Germany and elsewhere. The soil is classified primarily by the percentage of elutriable particles less than 0·01 mm. diameter, but the fraction 0·01–0·05 mm. is also taken into account. Fauser (1921) has drawn up a series of curves relating optimum drain distance to percentage of elutriable particles for different depths. These are based on practical scales drawn up by Canz, on the assumption that the optimum distance is a continuous function of the mechanical composition of the soil. Corrections are also introduced to take into account the percentage of calcium carbonate and of humus, as well as external features such as climate and the slope of the land.

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[1] The great discrepancies which may occur between the subjective estimates of different drainage experts for the optimum distance on a given soil have been clearly demonstrated by two investigations on the subject in Germany and the United States, described by Zunker (1923) and Schildknecht (1929) respectively.

Many other methods of mechanical analysis have been applied to a more limited extent to drainage problems, among which may be mentioned Zunker's sedimentation method (1926), Krauss's pipette method (1925), and several modifications of the original elutriation method. Mitscherlich (1923) has used the hygroscopicity and Janert (1931, 1933) the heat of wetting of the soil. The specific surface of the soil, determined either from its mechanical analysis or from its permeability in the structureless state, has been used by Zunker (1926, 1932) for the same purpose. The relation between the optimum drain distance in any soil, as accepted in practice, and its specific surface, has been expressed by him (1921) by means of several empirical formulae. There are also many methods of soil classification which have been used in other branches of soil science and which might be successfully applied to drainage, but the consideration of these lies outside the scope of the present work. Particular reference may be made, however, to Schofield's method (1933 *a*, *b*) of determining the base exchange capacity of the soil, which appears to be very suitable for the purpose. There is some evidence that the buffering capacity of the soil (derived from the values of the base exchange capacity at different hydrogen-ion concentrations) may provide further information about its drainage properties.

The methods of classification in common use have been compared with each other by Keso (1930), and by the UkBo[1]—a committee of German "Kulturtechniker." The results of the latter investigation are described by Zunker (1928). In both cases there was some indication that the methods of mechanical analysis led to a slightly more satisfactory classification than the hygroscopicity, but the differences were not very great. Keso also found that there were some soils in which all methods failed to give an adequate picture of the drainage requirements unless the pore space was also taken into account. The general conclusion which can be drawn from these and other similar investigations is that all the methods give very similar results, and that the choice between them depends primarily on considerations of cheapness and convenience. The two best methods from this point of view are undoubtedly the heat of wetting and the base exchange capacity. The chief disadvantage of the former is that it requires a constant-temperature room, and of the latter that the original apparatus is expensive,

[1] Unterausschuss für kulturtechnische Bodenuntersuchung.

although this difficulty can be avoided by substituting a titration for the conductivity determination. The working costs of both methods are very low and both are rapid and simple to work, Schofield's perhaps more so than Janert's.

All the laboratory methods of classification suffer from the limitation that they take no account of the soil structure. The drainage capacity of a given soil will depend largely on its structure, whereas the properties actually measured are not affected by it. Keso[1] gives examples of two Finnish soils with very similar mechanical compositions but differing structures, in which the optimum drain separation had been found by practical experience to be 13 and 35 m. respectively. Luedecke (1917) also described a number of medium and heavy German soils which, according to their mechanical analyses, should have been drained at 9–14 m. distance, but which in practice were either not in need of drainage at all or were successfully drained at 20–40 m. Janert (1932) has suggested a new soil constant—the degree of dispersion (Aufteilungsgrad) of the soil, defined as the ratio of the percentage of elutriable particles in the undispersed soil to the heat of wetting—which should give a measure of the soil structure. He has already applied it to the classification of soils for mole drainage, with promising results.

Several investigations have been made with a view to testing the validity of the assumption that the optimum drain distance is a function of some particular soil property. The method employed is to select a number of drained fields representing a wide range of soil types, in some of which the drain distance is too wide, in others approximately correct, and in others unnecessarily narrow. The property in question, *e.g.* the percentage of elutriable particles, is then determined for each field, and the value obtained is plotted against the drain distance in the field. Then if a simple relationship really existed between the optimum distance and the soil property, it should be possible to draw a smooth curve through the points thus obtained in such a way that all the points representing fields where the drainage system was just right lay on the curve, all where the distance apart was too narrow lay on one side of it, and all where it was too wide on the other. In practice it is known that certain other factors such as the drain depth, annual rainfall and slope of the land play a part in determining the optimum distance. Hence, if the required relationship is to be brought out, it will be necessary either to select fields where all these extraneous factors are approximately the same, or else to correct the actual distances for their influence. The latter method is generally used but is unsatisfactory, since the required corrections are not known accurately and in some cases are purely speculative. Janert (1933) gives a list of the corrections which are generally accepted.

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[1] *Trans. Sixth Comm. Int. Soc. Soil Sci.* (1933), vol. B, p. 233.

The method was first used by Breitenbach (1911), but the curve he obtained—relating drain distance with hygroscopicity—was of doubtful significance. A more elaborate investigation on the same lines was undertaken a few years ago by the UkBo (Zunker, 1928). Forty drained fields in different parts of Germany were selected, ranging from light sand to heavy clay, and including about equal numbers with adequate and inadequate systems. On each soil determinations were made of mechanical composition by four different methods, of hygroscopicity, heat of wetting, and soil permeability as measured by Freckmann and Janert's apparatus (1924). The value obtained in each case was plotted against the corrected drain distance. With the exception of the permeability method, which did not give satisfactory results, the classification obtained by each method was approximately the same. The point distribution when the corrected drain distance was plotted against the percentage of particles less than 0·02 mm. diameter is shown in Fig. 1. It will be seen from this that the selection of fields was unfortunate since all the heavy soils happened to be inadequately, and all the light soils adequately drained. The boundary curve decided on by the UkBo is shown in the figure, but under the circumstances it has very little significance. The investigation has been important, however, in showing that the tendency in Germany is to drain light soils too closely and heavy soils too widely. It should not be concluded that it is impossible to drain heavy soils satisfactorily. Both in England and on the Continent good results can be obtained in these, although generally with narrower distances than those shown in Fig. 1.

A third investigation was carried out by Schildknecht (1926) in Switzerland. He determined, by Kopecky's method, the mechanical composition of thirty-nine soils, of which seven were inadequately and the rest adequately drained. The point distribution in this case was more favourable and the boundary curve, which is shown for comparison (without the individual points) in Fig. 1, effected a good separation of the efficient and inefficient drainages[1].

The difference between the two curves is remarkable, and suggests that the Swiss heavy soils are unusually permeable. Schildknecht's relationship could certainly not be applied to the majority of wet heavy soils either in Germany or in England. It must be remembered, however, that Kopecky's method fails to distinguish between fine silt and clay and that the Swiss soils may have contained an unusually high proportion of the former. Robinson (1917, 1919) found that heavy soils occurring in regions of high rainfall in Wales had a much higher proportion of fine silt to clay than those occurring in the drier parts, and he suggested that this might be due to the clay colloid being unstable under high rainfall. The average precipitation in the part of Switzerland from which Schildknecht obtained his soils was over 40 in., and it is possible that the same explanation would apply here. In any case it may be concluded that a boundary curve is only likely to be significant if it is applied to soils which have developed under approximately similar conditions, and that no single curve will fit all soils.

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[1] The two curves are not strictly comparable, since Schildknecht's was based on the percentage of particles less than 0·01 mm. diameter. They should therefore be somewhat wider apart.

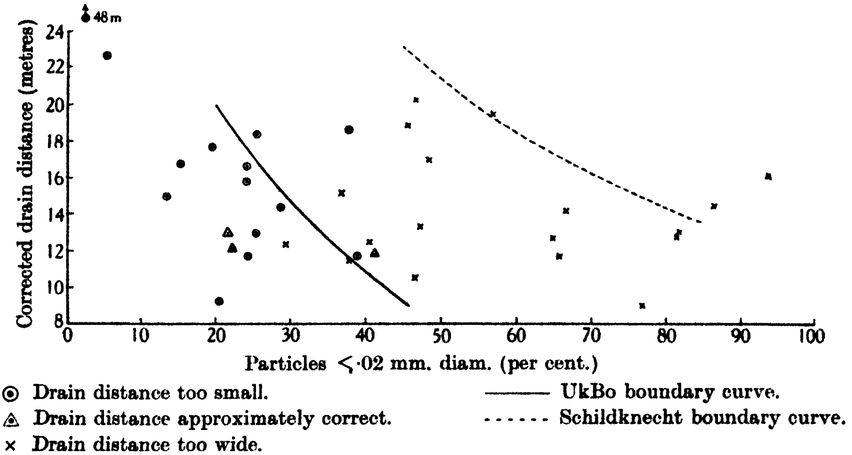

Fig. 1. Relation between corrected drain distance and percentage of particles <·02 mm. diam. Zunker (1928).

The chief limitation of the method lies in the difficulty of determining whether a given drainage system is satisfactory or not. In some cases this will be relatively easy, but generally it cannot be done with any confidence unless accurate data on the harvest yields for several years before and after drainage, together with the saving in cultivation costs, etc., are available. In each of the investigations described above, this information was lacking, and the decision as to whether a system was satisfactory was based on personal judgment only. Undoubtedly one of the most important directions in which drainage research could be developed would be the collection of statistics concerning the crop yields on drained soils and on undrained soils requiring drainage, together with the usual dates of sowing and harvesting, the length of life of the systems and the usual causes of failure. A certain amount of systematic work on these lines has been done in Bohemia (Kopecky, 1908; *Der Kulturtechniker*, 1930, p. 74). In Germany also a few investigations have been made, not always under sufficiently controlled conditions, among which may be mentioned those of Dilger (1900), Letsch (1919), Pfeiffer (1924), and Soergel (1932), but the subject, considering its fundamental importance if any real progress is to be made in drainage design, has on the whole been surprisingly neglected.

THE REMOVAL OF WATER FROM THE SOIL BY DRAINAGE.

For present purposes we may leave out of account the special conditions which arise where excess soil moisture is due to springs or seepage from higher levels, and consider simply the case where the water reaches the soil surface as atmospheric precipitation and percolates downwards into the drains. Many attempts have been made to obtain mathematical expressions for the rate at which it will enter the drains under these conditions, among the earliest of which are those of Colding (1876), Seyfert (1899), and Spöttle (1911). More recently Rothe (1924), Kozeny (1932, 1933) and Disерens (1933) have considered the question and, making similar assumptions but using somewhat different mathematical analysis, have arrived at identical formulae. The following account is based on Rothe's paper.

It is assumed that the soil is homogeneous, and that the rain water percolates uniformly downwards from the surface till it reaches the ground-water level, which then starts rising. When the ground water has risen above the drains it will start flowing into them, the rate of movement being greatest in their immediate neighbourhood and slowest half-way between two drains. The ground-water surface will therefore assume the shape shown in Fig. 2. A and B are drains, ACB the ground-water surface, and EF the soil surface. The higher the summit C rises, the more rapid will be the flow of water into the drains. Hence, if there is a constant supply of water percolating from the surface, the ground water between the drains will rise until it reaches a position of equilibrium at which the rate of flow into the drains is equal to the rate of downward percolation of the rain water. The ground-water surface will then remain stationary. The conditions determining the position of this steady state are calculated on the assumptions: (a) that the mean horizontal component (v) of the rate of flow through any cross-section PQ

is proportional to the slope (dy/dx) of the ground-water surface at P, and (b) that no water movement occurs through the subsoil below the drain level AB. Of these assumptions, (a) is based upon Darcy's law which is fundamental in all percolation studies and which states that the rate of flow of a liquid through a permeable medium is directly proportional to the pressure gradient. The exact application of this law to the present case would be very complicated, since the pressure gradient across PQ varies with the depth and is not in general equal to dy/dx, but the approximation may be reasonably close. (b) is only correct if the subsoil is impermeable, which will not generally be the case. It has been shown experimentally by Pennink (1907), and it is also clear theoretically, that a considerable amount of water normally travels to the drains *via* the subsoil below the drain level, in which case the present analysis does not apply.

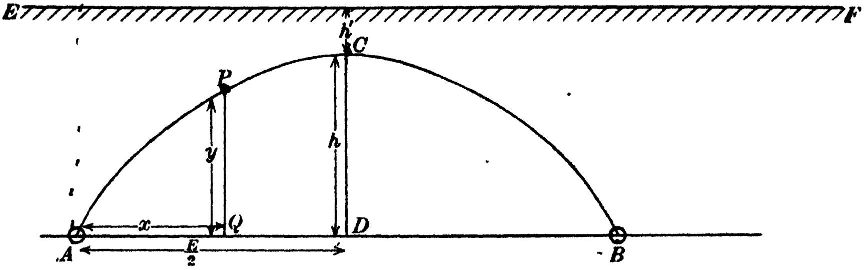

Fig. 2.

From (a)
$$v = k\frac{dy}{dx},$$

and
$$Q = ky\frac{dy}{dx},$$

where Q is the amount of water flowing in unit time through a cross-section PQ of unit thickness, and k is a constant representing the permeability of the soil.

Since the ground-water surface remains stationary, Q is equal to the amount of water percolating downwards from the soil surface in unit time between P and C. Therefore

$$Q = q\left(\frac{E}{2} - x\right),$$

where q is the amount of water percolating in unit time per unit area of soil surface.

Therefore $$ky\frac{dy}{dx} = q\left(\frac{E}{2} - x\right).$$

Therefore $$\frac{k}{q}.y^2 = Ex - x^2. \checkmark$$ $Ky^2 + x^2q = Exq$

on integrating. This is the equation of an ellipse with centre at D and semi-axes $\frac{E}{2}$ and $\frac{E}{2}\sqrt{\frac{q}{k}}$. Thus the summit of the ground-water surface reaches a maximum height h, where $h = \frac{E}{2}\sqrt{\frac{q}{k}}$. Hence if the drains are laid at a depth d the ground water will not rise above a depth h' below the surface, where $h' = d - h$. The equation may thus be rewritten

$$d - h' = \frac{E}{2}\sqrt{\frac{q}{k}}. \qquad \text{......(1)}$$

k is—at least in principle—determinable, and hence if q—the maximum rate of influx of water which the system will be required to deal with—is known, the depth and separation can be chosen in such a way that the ground water will never rise nearer to the surface than some specified distance h', which must be sufficiently great to prevent damage from waterlogging. It is generally assumed that h' should be not less than 70 cm. in arable land and 50 cm. in grassland.

Kozeny (1932, 1933) developed a similar formula, but he also took the diameter of the drain into account. He showed that unless this exceeded a certain critical value, which is a function of the four factors already considered, the drain would be unable to remove the soil water as fast as it arrived, and an accumulation above the drain would begin. It appears from his formula that the drain tiles in common use are not always wide enough to meet the demands which a particular system may impose on them.

The validity of the formula (1) can be tested by observing the actual shape of the ground-water surface between drains during wet weather. Data on this point are given by Spöttle (1911), Fauser (1921, 1923), Bartel (1928), Schlick (1918, 1928), Weir (1928), Thøgersen (1930), Simola (1930), Rothe and Philipp (1933) and Diserens (1933). Most observations were made on light or medium soils, but in a few cases, *e.g.* Fauser (1923) and Diserens, it was possible to make them also on heavy soils. It has been found, however, both in Germany (Zunker, 1928) and in Czecho-Slovakia (Janota, 1928), that a regular ground-water surface is rarely met with in heavy soils, so that the theory cannot generally be applied to these. In the lighter soils fairly regular curves have been obtained in which the ground-water level is lowest above the drains, and highest near the middle, but the chance variations due to soil inhomogeneity are usually too great to allow of any symmetrical curve being fitted to the surface. In some cases, *e.g.* Rothe and Philipp (1933), and Bartel (1928, p. 707), the curves are quite irregular and bear little relation to the position of the drain. A further difficulty in comparing the actual and theoretical form of the surface is that the formula only applies to a stationary state, whereas nearly all the published data refer to rising or falling ground water. The shape which the surface should assume under these conditions has not been worked out, but there is no reason to suppose it would be elliptical. It must be concluded that the mathematical formulation of the movement of ground water to drains is of doubtful theoretical validity, and that while it may have some practical application to homogeneous light soils it has none to heterogeneous or heavy soils. There are certainly very few cases in which the optimum dimensions of a drainage system could be calculated merely by substituting suitable values of k, q and h' in the formula. A knowledge of these factors is nevertheless of considerable value in designing a system, and many attempts have been made to evaluate them.

THE MEASUREMENT OF SOIL PERMEABILITY.

The following are a few of the more important methods that have been used:

(1) Kopecky (1904). A core of soil is removed by means of a special sampling cylinder with the least possible disturbance of its structure, and the rate of percolation of water through it is determined in the laboratory. This method has serious disadvantages, the chief of which are: (*a*) the presence of cracks or root channels may cause extreme variations in permeability from one sample to another, as has been shown by Hissink and Hooghoudt (1932); (*b*) a certain amount of distortion is found to occur when the sample is taken; (*c*) channels are liable to develop between the soil and the cylinder. The third difficulty has been overcome by Slater and Byers (1931) who coated the sides of the core with wax before using it.

(2) Freckmann and Janert (1924). A hole is bored into the soil by means of a steel cylinder and into it is introduced a perforated cylinder of the same diameter. This is filled with water to a constant height, and the rate of penetration into the soil is measured. The method has been tried out in the UkBo investigation already discussed, and by Schildknecht

(1926). It appears to be satisfactory for light soils, but in heavy ones the sides of the hole are liable to become puddled.

(3) Flodkvist (1931). An iron box consisting of four sides without top or bottom is hammered to about half its depth into the soil, a known quantity of water is poured in, and the time required for it to penetrate into the soil is measured. The most probable source of error is that channels may develop between the outside walls of the vessel and the soil, allowing the water to escape to the surface. This is avoided in a similar method of Dojarenko (1926)[1], in which two concentric cylinders are driven into the soil and filled with water to the same level. The outer cylinder acts as a guard ring and the actual measurements are made with the inner one.

(4) If there is ground water near the surface, the permeability can be measured by boring a hole below the ground-water level and measuring the rate at which the ground water flows into it. Methods employing this or some similar principle are described by Zunker (1930), Flodkvist (1931), Kozeny (1932) and Diserens (1933).

(5) Diserens (1933) determined the permeability of a soil over a relatively large drained area by substituting values in equation (1). h' was measured at several points within the area and q was calculated from the drain outflow. In a uniform soil with an impermeable subsoil and with a stationary ground-water level, this should be a good method, since errors due to chance soil variations would be smoothed out, but its applicability is very limited.

In addition to the soil inhomogeneity, a further difficulty arises, since the permeability varies considerably with the degree of saturation of the soil or, in a saturated soil, with the length of time for which the determination is continued. It is generally found in heavy soils that the permeability decreases steadily with time throughout the course of the experiment[2]. There appears to be no method at present which gives satisfactory results in all soils. In heavy soils the difficulties are still largely unsolved.

THE INFLUENCE OF HEIGHT OF GROUND WATER ON SOIL FERTILITY.

There is very little exact information as to the height to which the ground water may rise in a drained soil without causing serious damage. Bertram (1931) did some pot experiments on the subject, and found that temporary rises of the ground-water level during the summer, up to 50 cm. or less below the surface, had a very serious effect on the crop. For instance a rise from 80 cm. (the normal depth) to 50 cm. during a two-week period in June or July reduced the yield of barley on the average by nearly 50 per cent. A rise to 10 cm. depth under the same conditions reduced it by 70–80 per cent. The soil moisture conditions in pot experiments are not strictly comparable to those in the field, but the results leave no doubt as to the importance, in land suffering from high ground water, of designing a system which will ensure freedom from temporary waterlogging even under the wettest conditions. The optimum ground-water depth in most light soils appears to be about 1 m. or more below the surface, but little harm is done if it sinks lower except in very light ones[1]. In the Dutch sanddunes the optimum depth, according to Bijl (1930), is 50 cm. for arable land and 30 cm. for grassland. On medium and heavy soils the presence of ground water at any depth is not usually particularly advantageous.

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[1] Described by Krause (1931), who gives a full summary of Russian work on soil-moisture relations.

[2] See, *e.g.*, Burger (1924), Keso (1930).

THE MEASUREMENT OF DRAIN OUTFLOW RATES.

Measurements on drain outflow rates have been made, among others, by Bailey Denton (1859), Bartel (1928), Feilberg and Feilberg (1928, 1932, 1934), Prytz (1931), Flodkvist (1931), Rothe and Philipp (1933), and Nicholson (1934 *a* and *c*). Automatic recording is very desirable since the rate is often subject to large and rapid fluctuations, but there are many technical difficulties in designing an apparatus which will be reasonably accurate throughout a range of say 0·01–10 litres/sec. These have, however, been successfully overcome by Prytz (1931), Janert (1933) and Blackaby[2]. Janert's apparatus should be particularly useful owing to the wide range of outflow rates to which it can be accommodated, and to the fact that it can be built into the middle of a pipe-line, *e.g.* into a single minor if desired, instead of being situated at the outfall.

According to the simple theory, the outflow is determined by the height of the ground water between the drains. It should increase steadily until the maximum height is reached and then gradually fall off as the ground water is removed. Actual curves obtained by Flodkvist (1931) in clay soils after heavy rain do not bear out this view. The outflow rate after heavy rain increased rapidly to a very high maximum which might be many times greater than the theoretical maximum rate at which the ground water should be capable of reaching the drains. As soon as this maximum had been reached an equally rapid decrease began, which gradually flattened out after a few hours, when the rate had reached a value which could be considered as more normal for the system. From this it slowly decreased to zero. Other curves showing essentially similar features have been obtained by Rothe and Philipp (1933) on a medium loam, by Blackaby at Oxford, and by Nicholson on a heavy mole-drained pasture at Cambridge. The anomalous nature of these rates will be clear when it is considered that the normal outflow rate in permeable soils is usually reckoned at 0·65 lit./sec./ha., whereas the maximum rate found by Flodkvist in a heavy loam was 6·0 lit./sec./ha., by Rothe 12·0 lit./sec./ha. and by Nicholson 3·1 lit./sec./ha.

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[1] Data are given by Schneider (1925), Bijl (1927), Bertram (1931), Könekamp and Lehmann (1932), and Herzog (1932).

[2] *Engineering*, January 19th, 1934.

In order to account for this phenomenon Flodkvist has put forward a new theory of drainage in heavy soils. According to this, the undisturbed subsoil plays no important part in conducting water from the surface to the drain. The rain water penetrates the cultivated surface soil until it reaches the boundary between this and the subsoil. It then flows along this boundary, down the direction of greatest slope, until it arrives at a position vertically above a drain. The soil here, which had been taken out and replaced when the drain was laid, is considerably more permeable than the rest of the subsoil and the water percolates through it without difficulty into the drain. The high initial maximum of the outflow rate is accounted for as being due to water percolating directly down the permeable drain trench, and the lower but steadier subsequent flow as being due to the water which has had to travel laterally through the soil before reaching the trench. In order to test this theory Flodkvist determined the permeability of the soil in six different drained fields in Sweden, ranging from loam to heavy clay. In each field several determinations were made at points immediately above a drain and at corresponding points between two drains. In every case the permeability above the drain was much the greater, in some cases it was over 100 times as great as that between the drains. The theory was thus strongly confirmed. The effect was not due merely to a temporary loosening of the trench soil during replacement, since it was as strongly marked in a field with a 48-year-old system as in those with more recent ones. The increase in permeability may be due to a permanent change in the structure of the subsoil on exposure to weathering, or to the admixture with it, during replacement, of surface soil rich in humus, or to the increased root development which would result from particularly favourable drainage conditions above the drain. In any case it should be possible to increase the efficiency of drainage on heavy soils by taking steps to ensure that the drain trench remains permeable, *e.g.* by laying brushwood in it. This is sometimes done. It might also be possible to increase the speed of lateral flow of the water between the surface and subsoil by means of suitable cultivations.

Experiments similar to Flodkvist's were made by Nicholson[1] on a recently constructed mole drainage system on a heavy gault clay at Cambridge. These indicated that the drainage process in this soil was essentially similar to that postulated by Flodkvist, and that the greater part of the water which reached the mole travelled by way of the slit. It is not known how long the mole slits normally remain open, but they were plainly visible at the soil surface, during the recent drought, in a 16-year-old system on the University Farm[2].

Rothe and Philipp (1933) and Rozov (1932) repeated Flodkvist's experiments on considerably lighter soils, but failed to find any increased permeability above the drain. The permanent change of structure in the trench appears therefore to be chiefly characteristic of clays.

It is unlikely that the subsoil is completely impermeable even in heavy soils, since there may always be a certain number of cracks, cleavage surfaces or root channels to conduct water. This will be more especially the case after the drains have been functioning for several years, since the root range of the growing plants will then have been extended and more effective deep cultivations will have been made possible. The importance of these irregularities in the subsoil has not yet been satisfactorily determined, and it will doubtless vary greatly from one soil to another. In medium soils whose subsoils are fairly permeable but less so than the surface soil, the movement of water to the drains will probably be partly along the boundary between the two, and partly through the undisturbed subsoil.

THE RELATION BETWEEN DRAIN DEPTH AND DISTANCE.

According to the simple ground-water theory the optimum drain depth and distance are closely related to one another. It should be possible to obtain the same drainage effect with a wide deep system as with a closer shallower one. Drainage experts are agreed that this is the case in light soils, with the exception that in very light ones deep drainage may do harm by sinking the ground-water level too deep. In medium soils practical opinion appears to be doubtful as to the expediency of increasing the distance if the depth is increased, and in heavy soils it is generally against doing so. The only scientific data on the subject come from the Czecho-Slovakian experimental fields, and definitely support the view that in heavy soils the drainage effect of a close shallow system is not equivalent to that of a deep wide one. In the years when the former was most effective the latter was often least effective and *vice versa* (see p. 546). The Sixth Commission of the International Society of Soil Science considers, however, that in all soils an increase in depth justifies some increase in separation[1], and Zunker (1928) has recommended that for every 10 cm. increase in depth the separation should be increased by 10, 5 and 3 per cent. in sands, loams and clays respectively. Since no drainage expert can judge the optimum distance in any soil to 3 per cent. and only very doubtfully to 10 per cent. the suggestion—at least as regards heavy soils—must be considered as somewhat speculative. According to Flodkvist's theory the drain depth in heavy soils should have no influence on the optimum distance.

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[1] Unpublished.

[2] See Nicholson (1934 *b*). Further data on the life of mole drains are given in the same paper.

THE EFFECT OF DRAINAGE ON THE MOISTURE CONTENT OF THE SOIL.

Thøgersen (1930) compared the moisture content of drained and undrained land in the experimental field at Kvorning. He found that the undrained land had in general no higher and sometimes a much lower moisture content than the drained land, in spite of the fact that the crop yields on the latter were considerably greater. Hunt in America also found an increased moisture content in drained over undrained land[2]. It has frequently been observed that drained soils can withstand severe drought much better than undrained[3].

The distribution of moisture in drained fields has been studied in some detail by Solnar (1927) in Bohemia, and by Siebert (1930) in East Prussia. Solnar determined the moisture content of several different soils in spring and early summer, at different depths down to the drain level and at different distances from a drain. He found in all cases that at any given depth the moisture content tended to be greatest vertically above the drain. A typical example (omitting some of the sampling points) is given in Table II.

Siebert found that in wet weather the soil above the drain tended to be drier than the rest, and in dry weather wetter. Rozov (1932) compared the moisture content of a drained soil 1 m. from a drain with that mid-way between two drains on several occasions during summer and found that on the average the soil was a little drier near the drain. This would not necessarily apply, however, to the soil immediately above the drain.

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[1] *Trans. Sixth Comm. Int. Soc. Soil Sci.* (1933), vol. B, p. 245.

[2] Wheeler, W. H., *The Drainage of Fens and Low Lands* (1888), p. 37, London.

[3] See, *e.g.*, Stötzel (1902), Kopecky (1908), *Der Kulturtechniker* (1905, p. 199).

Table II. *The distribution of moisture in a drained soil* (Solnar).

Depth cm.	Moisture content (% by weight of dry soil)		
	Above drain	1 m. from drain	5 m. from drain
5	22·4	20·6	20·8
15	22·9	22·5	21·8
30	22·5	22·8	22·5
50	19·4	21·8	21·5
75	22·5	20·0	19·9
100	23·9	18·8	19·8
125	22·2	18·5	16·8
150	21·6	18·6	16·1
Average	22·2	20·4	19·9

The observed moisture conditions in drained fields are not such as would be expected on the straightforward theory of drainage, according to which the moisture content above the drains should always be less than elsewhere as long as there is any outflow, and should tend to become uniform throughout the field when the outflow stops. The drainage system thus appears to play a more active part in the soil economy than the mere removal of excess moisture. Four explanations of the increased moisture content immediately above the drains have been suggested:

(1) The soil above the drains is generally looser in texture owing to the fact that it has been dug out and replaced. There should thus be less upward capillary movement and consequently less loss by evaporation than in the compacter soil elsewhere. As against this, however, the losses by transpiration, which in the growing season are also important, will be greatest above the drain, since the most vigorous plant growth generally occurs there.

(2) The soil above the drains is usually mixed with surface soil when the drain trench is refilled. Consequently it has a higher organic matter content than the rest of the subsoil and therefore, probably, a higher water-holding capacity.

(3) The presence of the drain may lead to increased air circulation in the neighbouring soil, with consequent moisture deposition under suitable temperature conditions. In hot weather the cold air in the drainage system should tend to flow out through the outfall and draw warm air after it from the atmosphere into the soil, where, if the soil

temperature were low enough, it would be cooled below the dew-point. This view was suggested by Fauser (1930) as a result of observations by Seybold that a considerable flow of air out of the drains did occur in hot weather. Rothe and Philipp (1933) also detected strong outward currents from drain outfalls when the soil was dry. Janert (1933) has devised a sensitive apparatus for measuring and automatically recording the movements of air within a drain.

(4) The presence of the drain may enable rain water to percolate more readily into the soil. This theory, which has been advocated by Mezger (1931), presupposes that in an undrained soil the air would generally have difficulty in escaping after the surface had been saturated by heavy rain, and that it might to a greater or less extent become entrapped. Where this occurred, the water would be unable to penetrate to more than a limited extent into the soil layers containing the trapped air. It would therefore remain near the surface, and the soil air below it would become compressed. A large proportion of the surface water might thus be lost either by surface run-off or by evaporation, and the subsoil would tend to suffer from permanent water shortage. This would limit the root range of crops, and render them much more susceptible to drought. The effect of drainage under these conditions would be to provide an escape for the soil air through the drain. The water would then be able to percolate downwards without difficulty as far as the drain depth, causing a better distribution throughout the profile and less loss by evaporation or run-off.

This theory offers a very plausible explanation of the increased moisture content and drought-resisting capacity of drained soils in comparison with undrained. A certain amount of experimental evidence has been produced in support of it. For instance, both Ototzky (1921) and Dojarenko and Nekrassov (see Krause, 1931) observed the existence of a "dead layer" at a certain depth in some soils. This is a layer which tends to be permanently dry even when the soil above and below it is wet, and which thus shows exactly the condition postulated by the theory in cases where the subsoil air is unable to escape. King (1892), Ototzky (1921), and Thal Larsen (1932) made a number of observations on the well-water level in soils and found that it fluctuated much more violently after rain than was to be expected on the ordinary percolation theory. They attributed these fluctuations to an increase in the pressure of the entrapped soil air. It should be pointed out, however, that other explanations of both these phenomena have been put forward[1] and that

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[1] See especially *Trans. Sixth Comm. Int. Soc. Soil Sci.* (1933), vol. B, pp. 139–77.

Koehne (1929) made direct measurements with a manometer of the soil air pressure under a variety of weather conditions, but failed to detect any significant deviations of it from the atmospheric pressure. Mezger's theory is consequently not universally accepted.

If the air in a wet soil is isolated from the atmosphere to such an extent that pressure differences between the two could exist for an appreciable time, we should expect that the soil air pressure would be greater than atmospheric during periods of rapid barometric fall. The rate of outflow from a drain in the soil should increase under these conditions. This was found to be the case by Bailey Denton (1859) at Hinxworth. On two occasions during his observations there, the outflow rate from all drains increased although no rain had fallen, the average increase being 36·5 and 17·1 per cent. respectively. In each case a sharp fall in barometric pressure had occurred within the previous 24 hours. The same author (1883) also quoted observations by Beaumont to the same effect. King (1892) found that a fall in barometric pressure or a rise in temperature both increased the outflow rate. Rothe and Philipp (1933) observed increases in outflow rates which were not due to rainfall but were unable to correlate them with any climatic factors.

THE EFFECT OF DRAINAGE ON SOIL TEMPERATURE.

Comparisons of the temperature of drained and undrained land have been made in many different soils and at different seasons of the year, *e.g.* by Parkes (1845), Bailey Denton (1859), the Marquis of Tweeddale (Wheeler, 1888) and Kopecky (1908). In all cases the drained soil was found to be the warmer. The difference may vary from 1 to 5° C. or more, according to conditions. Solnar measured the distribution of soil temperature in several drained fields, concurrently with the moisture distribution determinations already discussed, and found that in most cases the soil tended to be a little cooler above the drains than between them, although the differences were generally less than 1° C. He attributed this to the higher moisture content above the drains.

THE EFFECT OF DRAINAGE ON THE PHYSICAL PROPERTIES OF THE SOIL.

Siebert (1930) determined the pore space of the soil in five fields with drainage systems from 11 to 20 years old and found in general that it was greatest vertically above the drains, *i.e.* in the old drain trench. Fauser (1933) found that in the 23-year-old field at Ellwangen the pore space in the subsoil above the drains was considerably greater than at the same depth elsewhere, although in the surface soil it was somewhat less above the drains than elsewhere. These results support Flodkvist's conclusion that the drain trench retains its improved structure for a long time. It was found at Ellwangen that the pore space between the drains had also increased in comparison with the original undrained soil.

Janota (1925) carried out a detailed investigation on the effect of drainage on the distribution of fine particles (less than 0·01 mm. diameter) and of calcium carbonate in a number of Bohemian soils. The soils were weakly podsolised loams and clays of the Brown Earth type. The illuvial B horizon, which contained considerably more fine particles than the A horizon, began about 1 m. below the surface. The drains had been laid in the B horizon. In the clay soils, and to a less extent in the loams, it was found that the percentage of fine particles in the A horizon tended to be smallest above the drains and greatest mid-way between them. In the B horizon it tended to be greatest above the drains and smallest between them. The effect of the artificial drainage had therefore been to intensify the natural leaching process, since the water travelling to the drains had carried down fine particles from the A horizon and redeposited them in the B horizon. The final result of drainage was to improve the structure of the surface soil but to make that of the subsoil worse in the neighbourhood of the drains. This eventually decreased their efficiency. Janota concluded that in heavy soils the drains should be laid just above the B horizon wherever possible. The clay which is washed down will then pass into the system whence, provided the slope is sufficient, it will be carried out by the drainage water. In medium soils the redeposition of clay in the B horizon does not decrease the permeability too greatly, and deep drainage is therefore permissible.

Table III. *Average content of fine particles* (<0·01 *mm. diam.*) *in* 13 *drained soils* (from Janota's data).

Depth	% of fine particles	
m.	1 m. from drain	Mid-way between drains
0·25	58·35	60·20
0·50	62·43	63·38
0·75	65·66	66·95
1·00	68·40	67·22
1·25	68·66	68·51

Table III, which has been calculated from Janota's data, shows the extent to which the distribution of fine particles may be modified by drainage. Each value in the table represents the mean of thirteen determinations, in different soils, of the percentage of fine particles at the given point relative to the drain. The drain depth varied from 1·4 to 1·8 m. in the different fields; the distance between drains varied from 9 to 15 m.

It is generally believed that artificial drainage on heavy land produces an improvement in structure which is not confined to the neighbourhood of the trench but which eventually spreads through the whole soil. This appears to be in accordance with practical experience, but there is little exact information as to the nature of this improvement. Fauser (1909) examined the changes in visible structure produced by several old but still effective drainage systems in a heavy clay soil. The subsoil in which the drains had been laid was a hard unweathered slate with a high percentage of calcium carbonate. In each case it was found to have been completely weathered and to have developed a fine crumb structure extending down to the full drain depth, to a distance of about 1 m. on either side of the drain. The weathering extended laterally to a diminishing extent for several metres. Fauser (1910 *a*, 1911) subsequently examined an old system on a clay soil of a different type, but was unable to find any significant alteration in structure due to drainage.

The great structural changes found by Fauser in his earlier investigations are undoubtedly somewhat exceptional. In most heavy soils the improvement is probably due chiefly to the fact that plant roots and earthworms can penetrate more deeply into the subsoil, which consequently becomes broken up, organic matter is added to it, and its permeability is increased. There is, however, in the opinion of the present writer, a tendency to exaggerate the effect, or at all events the rapidity with which it develops. Kozeny (1932) has put forward a theory of drainage which requires that the permeability of heavy soils should be able to increase by well over ten thousandfold in a few years after drainage. He attributes the increase primarily to the loose packing of the soil in the drain trench, which allows the soil between the drains to expand sideways during frost. On thawing again it will not contract to its original position, but the excess pore space originally in the trench will have distributed itself more evenly throughout the rest of the soil, producing a general increase in permeability. It should be pointed out, however, that heavy soils can be successfully drained in England, although frost rarely reaches the subsoil[1].

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[1] During the past 18 years at Rothamsted the frost has penetrated to a depth of 12 in. under bare soil on one occasion only (February 1929).

The only conclusion as to structure which can be regarded as established for a wide variety of soils is that the drain trench itself retains an increased pore space and a higher permeability than the rest of the soil. Other important structural changes may, and probably do, occur as a result of drainage, but further investigations as to the nature of these are required.

I wish to express my thanks to Dr Janert and Prof. Zunker for much helpful advice and for the facilities which they gave me for studying these problems in their Institutes for Kulturtechnik in Leipzig and Breslau respectively; and to Dr Janota for information concerning drainage research in Czecho-Slovakia.

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NUTRITIVE VALUE OF PASTURE.

XI. THE COMPOSITION AND NUTRITIVE VALUE OF WINTER PASTURAGE.

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Introduction.

For several years past investigations have been carried out in this Institute with the object of securing data concerning the yield, composition and nutritive value of pasture herbage under a variety of systems of grazing (1). These investigations have been restricted to the study of pasturage during the spring, summer and autumn. No attempt has been made to elucidate the nutritional characteristics of pasture grass during the winter season; nor is there available in the literature of the subject, so far as the writers are aware, any data respecting the feeding value of winter pasturage. It was with a view to filling in this gap in nutritional knowledge that the experiments to be detailed in the present communication were undertaken.

Writing in 1927, J. G. Stewart (2) states that while, on the whole, farmers do not suffer from the lack of summer grass, there are few who could not make good use of more and better winter grass. It should not be difficult to extend considerably the practice of winter grazing in those southerly counties that so frequently enjoy mild, open winters. He stresses the desirability of building up good winter pasture for the purposes of the sheep farmer, since with abundant winter and early-spring keep available, the grassland sheep farmer would be able to participate in the higher spring prices incidental to the early fat-lamb trade instead of being compelled to carry his stock through the summer and finally sell in a restricted and therefore glutted autumn market. Moreover, a farm heavily stocked throughout the winter with breeding animals that bring their young in the New Year is not likely to be understocked when the normal flush of grass has to be dealt with in May and June. The same writer emphasises the point that for winter grass a plentiful supply of available nitrogen is essential, and so long as nitrogen is balanced up with phosphate, potash and, where necessary, lime, and the soil is free draining, properly grazed and hoof cultivated, there is no danger of clover being suppressed. Although growth in winter is naturally controlled largely by temperature, the retarding effect of low temperature may be mitigated by generous manuring before growth normally slows-up and by the use of shelter belts. There is every likelihood of more and more wintering of stock out-of-doors, if only to ensure that animals get more sunlight, and for out-wintering, shelter is indispensable; but, as the writer points out, shelter belts are just as necessary in summer for shade and for checking the evaporation induced by drying winds.

W. A. Stewart (3) discusses the utilisation of winter grass for the outdoor wintering of dry in-calf cows and store cattle. By periodic weighings taken over a number of seasons, he was able to show that dry in-calf stock, on grass and lying out, increase in weight up to about the end of October, more or less maintain weight in November, and from then onwards lose weight unless they receive other food in addition to the grass. On the sort of land that is just below being first class, it is therefore advisable to feed some extra food from late October onwards. Where the feeding value of the grassland is not so good, it may be necessary to provide the extra food earlier. The same writer records the practice of a Northamptonshire beef producer of buying Shorthorn-Galloway cross-heifers in the autumn. The heifers, which are from 14 to 18 months old at the time of purchase, are wintered out-of-doors on grass, entirely without shelter, and from December onwards are given a limited amount of fodder, but no roots or concentrated food. They stand the winter well and quickly improve in condition when the grass becomes plentiful.

PLAN OF PRESENT INVESTIGATION.

Although W. A. Stewart makes no reference to the actual composition and nutritive value of winter grass, it is clear from his observations that the yield of such grass is insufficient to support store cattle throughout the winter, and that it becomes necessary to supplement the pasturage with roughage at a fairly early stage of the winter season. The amount of grass that is available for grazing during the winter months is determined mainly by three considerations: (1) The character of the weather in autumn and early winter. Since the soil in an ordinary season is abundantly supplied with moisture at this period of the year, the meteorological factors that control the growth of grass are temperature and sunshine. (2) The presence in the soil of readily available manurial reserves, so that the grasses may thereby be enabled to take the fullest advantage of spells of weather that are favourable to growth. (3) The time of the season at which summer grazing is discontinued. Obviously the amount of winter keep on a pasture will be much greater when unchecked growth is permitted from, say, the end of July, than when stock are allowed to continue grazing until the end of September. Not only is the interval of unchecked growth longer in the first case, but the pasture has the benefit of the favourable meteorological conditions of August, a time of the season when a small secondary flush growth is usually experienced.

The pasture used for the present work was that on which the investigations into the influence of the intensity of grazing on the yield, composition and nutritive value of pasture herbage have been carried out (1). The soil is of a light, sandy nature, and the comparative dryness of the field during winter renders it suitable for purposes of out-wintering stock. The treatment of the area during the several years prior to this experiment has ensured the presence of adequate reserves of chalk, potash and phosphate in the soil.

During the summer of 1932 the pasture was divided into three plots, 1, 2 and 3, measuring 0·29, 0·38 and 0·47 acre respectively. The herbage on plot 1 was held in check until July 31st by cutting with a motor lawn-mower at monthly intervals. On this date a dressing of neutral sulphate of ammonia was applied to the plot at the rate of 1 cwt. per acre, and the area was then permitted to grow unchecked until December, during which month the yield, composition and digestibility of the herbage were determined. The treatment of plots 2 and 3 was the same excepting that monthly cutting was discontinued at the end of August on plot 2 and on plot 3 at the end of September, the dates at which the herbage on these plots was submitted to investigation being January 1933 (plot 2) and February 1933 (plot 3). On these three plots, therefore, the yield, composition and nutritive value were determined of pasture herbage produced over the following growth periods: (1) end of July to December; (2) end of August to January; (3) end of September to February. In addition, during the previous winter (1931–2), an investigation under similar conditions was carried out on pasture herbage produced during a growth period extending from the end of October 1931 to the following March. In this case, owing to the smaller growth that was possible during these winter months, it was necessary to devote the whole of the area (1·14 acre) to the trial. For convenience, however, this area will be described as plot 4 in the account that follows.

In both years the winters were mild and open, the conditions as a whole being such as to enable the nutritional possibilities of winter grazing to be studied under the most favourable conditions. No heavy falls of snow occurred in either season, so that there was never any difficulty in cutting the herbage for feeding to the sheep in the digestion trials. Some idea of the conditions may be gained from the summary of meteorological data in Table I, but further details will be given when the influence of weather conditions on the palatability and digestibility of the herbage is dealt with.

Table I. *Summary of meteorological data for the growth periods of 1931–2 and 1932–3.*

	October		November		December		January	
	1931	1932	1931	1932	1931			
Total rainfall (in.)	0·63	3·73	2·10	2·50	0·91	0·35	0·73	1·13
Total sunshine (hours)	119·0	91·6	64·1	44·0	49·9	61·0	48·2	72·5
Mean max. daily temp. (° F.)	57·0	55·5	51·5	48·4	46·0	46·6	48·4	41·2
Mean min. daily temp. (° F.)	40·4	42·0	39·5	39·1	36·6	36·2	36·2	30·6

	February		March		August	September
	1932	1933	1932	1933	1932	1932
Total rainfall (in.)	0·22	1·31	1·26	1·56	2·54	1·66
Total sunshine (hours)	64·9	98·2	147·1	190·9	185·4	119·8
Mean max. daily temp. (° F.)	42·3	45·8	48·8	55·3	74·5	64·8
Mean min. daily temp. (° F.)	31·7	34·5	31·1	38·0	55·4	48·1

Pure-bred Suffolk wethers, aged 18–24 months, were employed for determining the digestibility of the winter pasture herbage. The daily ration supplied in the first trial (March 1932) was 5000 gm., an amount that was reduced to 4000 gm. per day in the trials of the following winter. All food residues were weighed back and analysed. The herbage was cut by means of a motor lawn-mower, except on those occasions when the grass was too long to be secured in this way, as in the trial conducted during December 1932, in which case it was necessary to employ the scythe. Owing to the conditions of cutting, the grass was frequently contaminated with a small amount of soil. All the yield and composition data given in this paper, however, have been corrected to a soil-free basis by the method described in an earlier communication (4). The uncorrected figures for composition may readily be calculated from the data of the digestion trials in the appendix.

Growth period 1 (end of July 1932 to December 1932).

The herbage on plot 1 was allowed to grow unchecked from the end of July until December, at which date the area was covered by an essentially *leafy* growth, consisting, in the order of importance, of perennial rye-grass, red fescue, creeping bent, cocksfoot, Yorkshire fog and rough-stalked meadow grass. The leaf of wild white clover was but sparsely represented in the herbage, but moderate amounts of burnet and yarrow were to be seen. The height of the herbage varied from 4 to 9 in., with tufts of cocksfoot up to 12 in. It had obviously been affected by recent and contemporary frosts, and although the rye-grass and fescue presented, on the whole, a verdant appearance, many of the blades were brown tipped; in particular, the cocksfoot tufts were very browned. As a consequence, the whole growth had a somewhat coarse appearance, although, for the time of year, it would have been considered very satisfactory by the practical man.

Table II. *Comparison of composition and feeding value of winter pasturage (December) and early spring pasturage of similar height, botanical composition and stage of growth.*

	Winter pasturage (present trial)	Fore-flush growth (5)
Period of unchecked growth ...	End of July to Dec. 1932	1 month before cutting
Date of cutting	Dec. 3–16, 1932	Apr. 15–28, 1930
	%	%
Composition on basis of dry matter:		
Crude protein	15·62	23·52
Ether extract	2·77	3·43
N-free extractives	51·75	45·90
Crude fibre	21·84	17·72
Ash	8·02	9·43
True protein	13·15	22·03
"Amides"	2·47	1·49
Lime (CaO)	1·04	1·30
Phosphoric acid (P_2O_5)	0·72	1·04
Moisture as cut	77·83	80·30
Digestion coefficients:		
Organic matter	68·7	83·4
Crude protein	62·5	82·1
Ether extract	28·0	42·4
N-free extractives	76·4	87·1
Crude fibre	59·7	83·7
Digestible composition and nutritive value (dry matter basis):		
Digestible crude protein	9·76	19·31
,, ether extract	0·78	1·45
,, N-free extractives	39·54	39·98
,, fibre	13·04	14·83
,, organic matter	63·12	75·57
Starch equivalent	56·47	70·60
Nutritive ratio	5·60	3·90

In attempting to assess the influence of winter conditions on composition and feeding value by instituting comparisons between this growth and summer herbage, the freedom from stemminess of the winter herbage must be kept in mind. Despite the long period of unchecked growth, it was comparable, in respect of height, botanical character and stage of growth, with *fore-flush* herbage obtained under a system of *monthly* cuts. A study of such herbage was made on the same pasture during the 1930 season (5), in which experiment the fore-flush growth in the second half of April varied in height from 4 to 8 in., was represented almost entirely by leafage and consisted mainly of creeping bent, perennial rye-grass, red fescue, Yorkshire fog, rough-stalked meadow grass and cocksfoot, while wild white clover was present in only small amount. Indeed, the main distinction between the two growths was that the spring grass was growing actively and had a good colour, whereas the winter herbage was frost-tipped and was displaying no signs of active growth. The results obtained in the present trial for the composition, digestibility and feeding value of the winter herbage are recorded in Table II, which also includes corresponding data for the comparable fore-flush herbage of 1930.

Comments on Table II.

Despite the similarity, to the eye, of the winter and early spring growths, very pronounced distinctions in composition and digestibility are readily discernible from the data in Table II. The winter grass was not only markedly poorer in both crude and true protein, but also contained distinctly higher percentages of crude fibre and N-free extractives. It will be noted further that the winter herbage was less rich in lime and phosphoric acid, although the depression of the lime value cannot be attributed to an effect of wild white clover, since the amount of clover in both growths was very small.

The difference between the two growths becomes even more pronounced when the data from the digestion trials are compared. The spring herbage displayed a very high digestibility, whereas that of the winter growth was poor by comparison. This finding is best brought out by the digestion coefficients of the organic matter in the two types of herbage, the spring value being 83·4 per cent. as against the winter value of 68·7 per cent. In the case of every constituent, the digestion coefficients for the winter grass were very significantly lower than the corresponding values for the spring herbage, the difference being especially notable in the cases of crude protein (82·1 as against 62·5 per cent.) and crude fibre (83·7 as against 59·7 per cent.). Despite its leafy character, the winter grass had clearly undergone a considerable degree of lignification. The inferiority of the winter grass is further emphasised by its relatively low content of digestible organic matter (63·1 per cent. of the dry matter as against 75·6 per cent. for the spring grass) and starch equivalent (56·5 per cent. as against 70·6 per cent.). The relatively low digestible protein content of the winter grass is also very striking, the percentage, on the basis of dry matter, being only 9·8 per cent. as against 19·3 per cent. for the spring grass.

It must be concluded, therefore, that a leafy winter growth may closely resemble a spring growth in respect of mixture of grass species, height and stage of growth and yet be very definitely inferior in composition, digestibility and feeding value. Evidently stage of growth is not the sole factor that determines the composition and digestibility of pasture herbage, since if this were so, the winter and spring growths considered above should have been almost equal in these respects. The meteorological conditions, particularly in relation to their influence on the rate of growth, must also be taken into account. In the case of the winter herbage, the low temperature of the season and the frosts of December had brought growth to a standstill; on the other hand, under the conditions of the spring trial, the herbage was displaying vigorous growth. These contrasting conditions must be held responsible for the observed differences in composition and digestibility. With herbage in active growth, the onset of lignification is postponed until the plants have passed the vegetative stage of development; but with winter herbage, where growth, as a consequence of adverse temperature, has slowed down or ceased altogether, and where no fresh food material is being transported from the soil into the herbage plants, it would appear that a reorganisation of the material already in the plants takes place as a means of defence against the inclement conditions. These changes result in a partial lignification of the fibrous constituent and a consequent lowering of the digestibility and nutritive value, and this despite the fact that the grasses have not progressed further than the leafy stage.

It is interesting to note that similar effects on composition and digestibility have been noted with summer grass when the incidence of severe drought has arrested the growth processes in the pasture plants. It has been shown (5) that under a system of monthly cuts no evidence of lignification is manifested provided the weather conditions are such as to encourage active and continuous growth, but that if lack of rainfall leads to a slowing-up in the rate of growth, then a stage may be reached, within the monthly interval between successive cuts, when the lignification processes will begin to modify the character of the herbage. This effect is intensified during a drought of sufficient duration to cause the herbage to become parched and brown. Transportation of food material from the soil becomes impossible owing to lack of the necessary moisture and, as a consequence, the vegetative phase of plant development comes to an untimely end. A process of re-elaboration of the material already in the plant sets in, clearly to enable the grasses to combat successfully the adverse conditions, and this leads to the gradual lignification of the cellulose in the cell walls and a lowering of the digestibility of the herbage. These changes are accompanied by a decided falling off in the percentage of crude protein, a slight increase in the fibre, an abrupt rise in the percentage of lime and a decline in the phosphoric acid content. The effects produced by the cold of winter are clearly similar to those brought about by severe drought in summer, the main distinction being that summer drought raises the lime content whereas winter frosts cause it to be depressed. It appears therefore that the composition and digestibility of grass are not only to be related to the stage of growth at which the grasses have arrived, but also to the rate of growth as influenced by meteorological factors. The latter, however, have a predominant influence only in times of extreme cold and frost (winter) or severe drought (summer).

It was observed that the plot displayed a very satisfactory recovery after having been cut during the first half of December. Despite the frequent frosty periods of January and February, the area appeared green and lawn-like again at the end of February, being covered by a leafy growth of about 1½–2 in. in height. A number of unusually mild days during this period were mainly responsible for this good winter recovery.

GROWTH PERIOD 2 (END OF AUGUST 1932 TO JANUARY 1933).

At the time of the digestion trial in January the herbage on plot 2 was much less coarse than the herbage that had been cut from plot 1 in December. The bulk of the herbage was green and leafy, no stems being observed. The general height was from 2 to 4 in. with small areas up to 7 in. A proportion of the grasses was brown tipped by frost, but the healthier appearance of the cocksfoot in this plot as compared with that in plot 1 suggested that the younger plant is able to withstand the effects of frost more successfully than the same plant at a more advanced stage of growth. In the order of importance the grasses in this area consisted of fescues, perennial rye-grass, rough-stalked meadow grass, Yorkshire fog, cocksfoot and creeping bent.

Since in this trial the period of unchecked growth had not included the month of August, the herbage in plot 2 was distinctly less advanced than that investigated in the December trial. On the grounds of stage of growth and botanical composition, the following two growths, produced in past investigations on this pasture, afford a fair basis of comparison between the winter grass under investigation and grass grown during the normal pasture season: (1) Fore-flush herbage grown under a system of 3-weekly cuts (6). In this case the herbage was wholly leafy and was from 2 to 4 in. high. It was composed mainly of perennial rye-grass, creeping bent, red fescue, rough-stalked meadow grass and cocksfoot. It contained a fair proportion of wild white clover, which circumstance, together with its very active state of growth, constituted

Table III. *Comparison of composition and feeding value of winter pasturage (January) with spring and summer pasturage of similar height, botanical composition and stage of growth.*

	Winter pasturage (present trial)	Fore-flush growth (6)	Summer growth (5)
Period of unchecked growth ...	End of Aug. 1932 to Jan. 1933	3 weeks before cutting	4 weeks before cutting
Date of cutting	Jan. 2–20, 1933	Apr. 25 to May 8, 1928	July 5–18, 1930
	%	%	%
Composition on basis of dry matter:			
Crude protein	20·15	22·69	17·37
Ether extract	3·75	6·51	3·91
N-free extractives	46·37	46·47	48·92
Crude fibre	21·12	15·26	20·95
Ash	8·61	9·07	8·85
True protein	17·65	19·89	15·37
"Amides"	2·50	2·80	2·00
Lime	1·02	1·42	1·36
Phosphoric acid	0·73	1·01	0·98
Moisture as cut	75·60	78·90	71·50
Digestion coefficients:			
Organic matter	66·8	82·1	76·7
Crude protein	65·1	80·5	75·9
Ether extract	22·8	60·5	33·2
N-free extractives	75·8	86·2	79·7
Crude fibre	61·3	81·1	78·6
Digestible composition and nutritive value (dry matter basis):			
Digestible crude protein	13·12	18·27	13·18
„ ether extract	0·86	3·94	1·30
„ N-free extractives	35·15	40·06	39·03
„ fibre	12·95	12·38	16·47
„ organic matter	62·08	74·65	69·98
Starch equivalent	55·31	72·72	64·30
Nutritive ratio	3·80	3·40	4·40

the main distinction between the winter and spring herbage. (2) July herbage obtained under a system of monthly cuts (5). The bulk of this growth was leafy in character and was from 2 to 5 in. in height. In the order of importance, it consisted of creeping bent, red fescue, perennial rye-grass, cocksfoot and Yorkshire fog. It was not growing very quickly, however, at this stage of the season, as the dry weather encountered during June had reacted adversely on the general vigour of the grasses. It was mainly distinguished from the winter herbage by its content of wild white clover, although the amount of this plant in the summer growth was only small.

The results that were obtained in the present trial for the winter herbage are compared in Table III with the corresponding data for the spring and summer herbage.

Comments on Table III.

A comparison of the results for the winter and spring grass brings out again the observations already recorded respecting the effect of winter conditions on the composition and feeding value of pasturage. Despite the similarity of the two growths from the botanical standpoint, the winter herbage was poorer in lime, phosphoric acid and ether extract, and was distinctly more fibrous than the spring grass.

In assessing the significance of the lime values, however, it should be remembered that the spring herbage contained a greater proportion of wild white clover. The winter herbage displayed, as in the December trial, an all-round inferiority in respect of digestibility and digestible composition, the values being indicative of a fair degree of lignification in the winter growth. This is further evidenced by the relatively low starch equivalent of the January grass, amounting to 55·3 per cent. (dry matter basis) as against 72·7 per cent. for the spring pasturage.

It will be noted that the crude protein content of the January grass (20·2 per cent. of the dry matter) was distinctly higher than that of the more advanced growth cut during the December trial (15·6 per cent.). Indeed, it was not far short of the value for the spring pasturage (22·7 per cent.), but owing to its poorer digestibility the comparison on the basis of digestible protein is distinctly less advantageous.

The comparison between the winter grass and the July herbage obtained by cutting at monthly intervals was by no means so unfavourable to the winter grass as is the case in the comparison with the spring pasturage. The summer grass, however, was suffering from the effects of the droughty weather that had prevailed in June and throughout the period of the trial in July. Growth was slow and the herbage had a thin, patchy appearance. It was secured in the mid-seasonal phase of low protein content, and it is noteworthy that the winter grass was actually richer in this constituent. This advantage is lost, however, if the lower digestibility of the protein in the winter grass is taken into account. Despite the adverse influence of drought on the summer herbage, the still stronger depressing effects of the slowing-up of growth by winter conditions are to be noted in the lower digestion coefficients (particularly in the cases of protein and fibre) of the winter grass and its significantly lower starch equivalent (55·3 per cent. on the basis of dry matter as against 64·3 per cent.).

GROWTH PERIOD 3 (END OF SEPTEMBER 1932 TO FEBRUARY 1933).

The herbage in plot 3 had been produced almost wholly under winter conditions, so that at the date of the digestion trial in February it was not very advanced in growth and consisted of a uniform, short, leafy growth from 1½ to 3 in. in height. The main grasses were red fescue, perennial rye-grass, rough-stalked meadow grass and Yorkshire fog, which together formed at least 80 per cent. of the total herbage. Cocksfoot and creeping bent were also present in small amount. The area had generally a green appearance, but a number of severe frosts in late January had caused many of the grasses to be tipped with brown, cocksfoot and the fescues being most affected and rough-stalked meadow grass the least. It was evident, however, that this younger, shorter herbage was able to withstand the effects of frost more successfully than the older, longer grass. Compared with a spring or summer growth of similar length and leafiness, the herbage in plot 3 had a rather unhealthy appearance, and an observer would have predicted that its palatability would be lower than that of corresponding spring or summer grass. This proved to be the case.

The data for the following growths have been selected from the results of previous investigations on the same pasture for purposes of comparison of the winter herbage with spring and summer grass: (1) Fore-flush herbage grown under a system of fortnightly cuts (7). This was a leafy and actively-growing herbage (2–4 in. in height), composed mainly of perennial rye-grass, rough-stalked meadow grass, meadow foxtail, cocksfoot and fescues, with some creeping bent and a moderate amount of wild white clover leaf. (2) July grass obtained under a system of 3-weekly cuts (6). This growth was almost wholly of a leafy character and was 1½–3 in. high. It contained creeping bent, perennial rye-grass, red fescue, cocksfoot, rough-stalked meadow grass, with a little Yorkshire fog and a fairly abundant amount of wild white clover partly in flower. The herbage at this time of the season had lost its early vigour of growth owing to the hot, rainless weather then prevailing. The comparative data in respect of composition and feeding value are shown in Table IV.

Table IV. *Comparison of composition and feeding value of winter pasturage (February) with spring and summer pasturage of similar height, botanical composition and stage of growth.*

	Winter pasturage (present trial)	Fore-flush growth (7)	Summer growth (6)
Period of unchecked growth	End of Sept. 1932 to Feb. 1933	14 days before cutting	21 days before cutting
Date of cutting	Feb. 1–18, 1933	Apr. 19 to May 3, 1927	July 8–17, 1928
	%		%
Composition on basis of dry matter:			
Crude protein	22·84	25·48	20·67
Ether extract	3·91	7·55	6·05
N-free extractives	44·47	43·46	46·12
Crude fibre	19·82	14·05	17·92
Ash	8·96	9·46	9·24
True protein	19·82	22·11	18·30
"Amides"	3·02	3·37	2·37
Lime	1·27	1·44	1·63
Phosphoric acid	0·77	1·17	1·06
Moisture as cut	71·20	79·00	74·20
Digestion coefficients:			
Organic matter	71·2	82·3	78·6
Crude protein	71·6	81·7	79·4
Ether extract	47·5	66·0	48·4
N-free extractives	75·4	85·6	82·2
Crude fibre	71·0	82·1	78·5
Digestible composition and nutritive value (dry matter basis):			
Digestible crude protein	16·35	20·82	16·41
„ ether extract	1·86	4·98	2·93
„ N-free extractives	33·53	37·20	37·91
„ fibre	14·07	11·54	14·07
„ organic matter	65·81	74·54	71·32
Starch equivalent	59·98	73·75	67·82
Nutritive ratio	3·20	2·90	3·60

Comments on Table IV.

The February grass on plot 3 was somewhat less advanced in growth than the grass obtained from plot 2 in January. This was reflected in its somewhat higher protein and lower fibre content. Indeed, the disparity in composition and digestibility between the winter herbage and the spring and summer herbage of similar external characteristics was distinctly less marked than was the case in the January and December trials. The fibre digestion coefficient had improved to 71 per cent., compared with 61 per cent. for the January grass, a result that points to a lesser degree of lignification in the February herbage. Similar improvements are also discernible in the digestion coefficients of the crude protein, ether extract and total organic matter, although in the case of the N-free extractives the value of the digestion coefficient remained almost unaltered throughout the three feeding periods so far dealt with.

It might be that this improvement of the winter herbage in relation to corresponding spring and summer grass was to be ascribed to a speeding up of the growth processes in the grasses as a consequence of the setting-in during February of more favourable meteorological conditions. This was not the case, however, since apart from a spell of relatively mild weather from February 4 to 9, frosty weather characterised the second half of January and most of February. It must be concluded, therefore, that the depressing influence of winter conditions on the composition and digestibility of pasture herbage is less pronounced with short herbage than with longer grass in a more advanced stage of growth. This is in harmony with the observation, especially apparent to the eye in the case of cocksfoot, that the younger plant is better able to resist the "browning" effect of frost than the same plant at a more advanced stage of growth.

Despite what has been written, however, the data in Table IV show quite clearly that even with this shorter growth of winter herbage, the slowing-up of growth consequent on winter conditions had resulted in a definite lowering of digestibility and feeding value. This is particularly conspicuous when the results for this herbage are compared with the corresponding data for the actively-growing spring herbage. Even in the case of the July herbage of similar height and botanical characteristics, the depression is still noticeable, though in a lesser degree, despite the circumstance that the rate of growth in the summer herbage had been affected very adversely by the droughty weather then prevailing.

GROWTH PERIOD 4 (END OF OCTOBER 1931 TO MARCH 1932).

The winter of this fourth trial (1931–2) was, on the whole, of even a more open character than that during which the trials already described were carried out (1932–3). This observation applies particularly to the period October 1931 to the end of January 1932. Only in February was typically cold winter weather experienced. This month was also one of exceptional drought. March was characterised by cold nights and fairly warm days, the amount of rainfall during the first half of this month again being very small.

Despite its long season of unchecked development, the herbage at the time of the March digestion trial presented a rather lawn-like appearance, being no more than 1½–2 in. in height. It was wholly leafy in character and contained very few weeds. Its general appearance was green and fresh, but cocksfoot here and there was somewhat browned by recent frosts and, indeed, most of the other grasses were also slightly brown tipped. The main species in the pasture plot were red fescue, cocksfoot, rough-stalked meadow grass, perennial rye-grass, creeping bent and meadow fescue. Leafy clover was also represented in the herbage, but made an almost negligible contribution to the yield of mown herbage.

In attempting to assess the effect of season on the composition and digestibility of this winter growth, the comparison must obviously be

Table V. *Comparison of composition and feeding value of winter pasturage (March) with spring and summer pasturage of similar height, botanical composition and stage of growth.*

	Winter pasturage (present trial)	May pasturage (4)	Late-July pasturage (4)
Period of unchecked growth	End of Oct. 1931 to Mar. 1932	7 days before cutting	7 days before cutting
Date of cutting	March 1–21, 1932	May 4–21, 1925	July 24 to Aug. 10, 1925
	%	%	%
Composition on basis of dry matter:			
Crude protein	21·41	26·37	21·22
Ether extract	4·35	5·36	5·67
N-free extractives	52·45	44·37	46·45
Crude fibre	13·76	13·46	17·68
Ash	8·03	10·44	8·98
True protein	18·41	20·75	18·45
"Amides"	3·00	5·62	2·77
Lime	1·53	1·58	1·68
Phosphoric acid	0·78	1·14	0·90
Moisture as cut	69·00	80·50	71·70
Digestion coefficients:			
Organic matter	76·8	83·6	74·4
Crude protein	71·6	85·4	76·6
Ether extract	54·5	60·0	47·9
N-free extractives	80·9	87·4	76·0
Crude fibre	76·1	79·2	76·0
Digestible composition and nutritive value (dry matter basis):			
Digestible crude protein	15·33	22·52	16·25
„ ether extract	2·37	3·22	2·72
„ N-free extractives	42·43	38·78	35·30
„ fibre	10·47	10·66	13·44
„ organic matter	70·60	75·18	67·71
Starch equivalent	67·85	72·86	63·56
Nutritive ratio	3·80	2·50	3·40

made with pasturage kept short and leafy by frequent cutting. The data for the following growths, obtained under a system of weekly cuts from the same pasture during the 1925 season (4), enable the comparison to be made, since in both cases the herbage resembled the March grass of the present investigation in respect of height and leafiness: (1) May pasturage obtained under a system of weekly cuts (4). This growth was of very good colour and was growing vigorously. It was composed mainly of perennial rye-grass, soft brome grass, rough-stalked meadow grass, meadow foxtail and fescues, and contained a higher proportion of wild white clover than was present in the winter herbage. (2) Late July pasturage obtained under a system of weekly cuts (4). In this case the pasture was suffering severely from the effects of mid-seasonal drought and heat, and the herbage was just displaying signs of recovery under the influence of recent rain. A good deal of cocksfoot was included in the earlier samples of this period, this species showing the quickest recovery. This was quickly followed by rye-grass, but clover did not grow sufficiently fast for any significant amount to be included in the mown herbage.

The essential data for comparing the winter grass with the spring and summer growths are recorded in Table V.

Comments on Table V.

In the discussion of the results for the February herbage (see Table IV) it was pointed out that the disparity in composition and digestibility between the winter herbage and the spring and summer herbage of similar external characteristics was distinctly less marked than was the case in the January and December trials. The data in Table V show that this applies with even greater emphasis to the winter herbage grown over the period from the end of October to the following March, and that the short, leafy March pasturage displayed most of the characteristics associated with similar herbage grown during the normal pasture season.

The data in Table V for the May pasturage represent young grass at its phase of maximum protein content and digestibility. Keeping this in mind, the results for the March grass must be considered highly satisfactory. The winter herbage was as low in fibre as the spring grass, and, judging from its fibre digestion coefficient, which had risen to 76 per cent., it was almost as non-lignified. Its protein content, and the digestibility of its protein, were distinctly lower, and these characteristics, together with its lower ash and phosphate content, were probably the main manifestations of the different climatic conditions under which the two growths had been produced. In almost every other respect the short, leafy grass produced under winter conditions, while not displaying actual equality, gave evidence of its kinship with the short, leafy grass grown under spring conditions. Indeed, the results for the July grass, produced also under a system of weekly cuts, show that a hot, droughty summer may cause a greater deviation from the maximum values of the spring grass than is evidenced by similar grass produced by unchecked growth over the November-March period. The digestibility of the protein in the winter-grown herbage was certainly somewhat lower than that of the July grass, but in several important respects the March grass displayed a slight, but definite, superiority, this being evidenced in its content of total digestible organic matter (70·6 per cent. of the dry matter as against 67·7 per cent.) and of starch equivalent (67·9 as against 63·6 per cent.).

To what factors is this close approach of the winter herbage to the corresponding spring and summer herbage to be attributed? It has already been concluded that winter conditions cause a smaller deterioration in the composition and feeding value of short, leafy grass than is the case with a longer and more advanced leafy growth. This may account for the very satisfactory composition and digestibility of the very short, leafy herbage investigated in the March period, especially since night frosts occurred frequently during the course of the trial. It is felt, however, that this cannot be the whole explanation of the closeness of the approach of this winter-grown herbage to the young, leafy herbage of spring. It seems feasible that this improvement is the earliest manifestation of the strong growth impulse that becomes evident to the eye during April in an abundance of new growth on the pasture. This impulse is possibly able to make itself felt during the first half of March and, although not as yet strong enough to occasion much actual growth of new tissue, is sufficient to awaken physiological activity within the plants and modify, in preparation for new growth, the chemical character of the plant tissues. The herbage plants in this process lose the partially-lignified character imposed on them by winter conditions and take on the non-lignified nature associated with spring. If this hypothesis be accepted, the development in this particular trial would have received encouragement from the unusual warmth of the March days, which contrasted with the cold experienced during the nights.

That such an explanation is not at all improbable is borne out by the results that have been obtained in the investigation of the influence of manurial treatment on the yield and composition of pasturage. In this work (8) the winter growth has always been mown in late March and early April, and this treatment has been followed by cutting the plots at monthly intervals. It is significant, in relation to the hypothesis put forward in the preceding paragraph, that the winter growth obtained in this way is characterised by a higher protein and lower fibre content than the monthly spring cuts following the removal of the winter herbage.

Table VI. *General summary of experimental results.*

Growth period	End of July 1932 to Dec. 1932	End of Aug. 1932 to Jan. 1933	End of Sept. 1932 to Feb. 1933	End of Oct. 1931 to Mar. 1932
	%	%		%
Composition on basis of dry matter:				
Crude protein	15·62	20·15	22·84	21·41
Ether extract	2·77	3·75	3·91	4·35
N-free extractives	51·75	46·37	44·47	52·45
Crude fibre	21·84	21·12	19·82	13·76
Ash	8·02	8·61	8·96	8·03
True protein	13·15	17·65	19·82	18·41
"Amides"	2·47	2·50	3·02	3·00
Lime	1·04	1·02	1·27	1·53
Phosphoric acid	0·72	0·73	0·77	0·78
Digestion coefficients:				
Organic matter	68·7	66·8	71·2	76·8
Crude protein	62·5	65·1	71·6	71·6
Ether extract	28·0	22·8	47·5	54·5
N-free extractives	76·4	75·8	75·4	80·9
Crude fibre	59·7	61·3	71·0	76·1
Digestible composition and nutritive value (dry matter ba				
Digestible crude protein	9·76	13·12	16·35	15·33
,, ether extract	0·78	0·86	1·86	2·37
,, N-free extractives	39·54	35·15	33·53	42·43
,, fibre	13·04	12·95	14·07	10·47
,, organic matter	63·12	62·08	65·81	70·60
Starch equivalent	56·47	55·31	59·98	67·85
Nutritive ratio	5·60	3·80	3·20	3·80
Yield of nutrient matter:				
lb. dry matter per acre	1787	931	576	339
lb. starch equivalent per acre	1009	515	345	230
lb. digestible protein per acre	174	122	94	52

Comments on Table VI.

The significance of the variation of the results in respect of composition and digestibility from period to period has already been sufficiently discussed, and attention must now be given to the data for yield in terms of dry matter, starch equivalent and digestible protein, since no matter how satisfactory winter herbage may be in regard to composition and nutritive value, it is imperative that the yield of grass should be reasonably ample if the results are to be of practical importance. In considering the data from this standpoint, it is desirable to emphasize again that the weather in both the winters of experiment was more than usually favourable to the production of out-of-season growth, and that for this reason the results probably measure the highest capacity of the pasture, under the conditions of the present trials, for production of winter grass. It may be noted, however, that the experimental pasture by no means belongs to the most highly productive type of grassland. During the 1930 season, for example, it yielded only 5365 lb. of dry matter per acre compared with 7996 lb. from a better type of heavy-land pasture on the same farm.

It will be seen from Table VI that although the herbage produced over the periods (1) end of September to February and (2) end of October to March displayed the best composition and feeding value, the yields in both cases were too low to have any significance in farming practice. Indeed, it would appear necessary to discontinue the grazing of pastures at the end of July if it is desired to produce an adequate amount of herbage for grazing during the winter months, at any rate under such climatic conditions as obtain in East Anglia.

Under these conditions the present pasture would have produced, for grazing in December, 1787 lb. of dry matter per acre, including 1009 lb. of starch equivalent and 174 lb. of digestible protein. To gain an insight into the practical utility of such a supply of winter pasturage, it may be noted that an acre of such grass would supply keep for a store bullock of 8 cwt. live-weight, consuming 20½ lb. of dry matter per day, over a period of 87 days. The ration so secured would supply 11·6 lb. of starch equivalent, from which must be deducted 5½ lb. for the animal's normal maintenance requirements. This would leave 6·1 lb. of starch equivalent for other purposes, and if 2¼ lb. be allowed for live-weight increase at the rate of 1 lb. per day, then the 3·85 lb. of starch equivalent still remaining should be ample for furnishing the energy expended in grazing and in the increased muscular activity induced by the cold conditions. The supply of digestible protein in the ration, namely, 2 lb., would be sufficient to cover all the animal's needs in this respect.

In the same way it can be shown that an acre of the grass produced in the growth period from the end of August to the following January would have supported the 8 cwt. store bullock over a period of 45 days. The ration in this instance also would have sufficed for live-weight increase at the rate of 1 lb. per day. In the cases of the grass produced from (1) the end of September to February and (2) the end of October to March, the bullock, grazing an acre of such winter herbage, would have found keep for only 28 and 16 days respectively, although, in view of the higher feeding value of the herbage, a higher rate of live-weight increase than 1 lb. per day would have been possible.

PALATABILITY OF WINTER PASTURAGE.

An outstanding observation in these winter grass feeding trials was the discovery that, compared with spring or summer grass, the winter herbage had a definitely unpalatable character. In the numerous digestion trials of spring and summer grass carried out in this Institute during the last ten years, no difficulty has usually been experienced in inducing the experimental sheep to consume a full ration of the herbage. Indeed, non-lignified grass has been found to be specially distinguished by its high palatability. Only in one instance have the animals shown a disinclination to consume the grass ration. This was in the June of 1927, when, following a remarkably hot, dry period of some weeks' duration, the dry matter of the grass had risen to the abnormally high level of 31·8 per cent.(7) Unpalatability in this case was directly attributable to the influence of drought. Apart from this isolated experience, however, no case has been noted of the sheep definitely refusing to eat pasture herbage during spring and summer.

The attitude of the experimental sheep to the winter grass rations left no doubt in the minds of the observers as to the relatively low palatability of such herbage. Four sheep were brought on to the grass ration at the beginning of the 1932–3 trials in December 1932. Not one of them displayed any liking for the herbage, and it was only by continuing the feeding for some days that it was possible to select two sheep able to consume sufficient of the herbage to ensure a satisfactory digestion trial. The same two sheep were employed in the January trial, and although consuming a satisfactory amount for the purposes of the trial, again displayed no signs of eagerness in feeding. Before the commencement of the third trial in February, both sheep were given a rest period on hay and concentrates. On attempting to resume the feeding of the grass ration, however, it was found that sheep XXII steadfastly refused to feed. This animal therefore was withdrawn from the experiment, its place being taken by one of the reserve wethers. That the refusal of sheep XXII to feed was due to its dislike of the winter grass, and not to ill-health, was evidenced by the eagerness with which it now ate its new ration of hay and concentrates.

There are probably several factors contributing to the unpalatability of winter pasturage, but it would seem from the results of the present investigation that frost, with its accompanying browning effect, is the most important. Moreover, the effect is not simply proportional to the degree of severity of the frost, but is also related to the stage of growth of the herbage at the time. For example, the herbage tested in the trial of March 1932 had been subject to the influence of very severe frosts in the period immediately preceding. Night frosts were also prevalent during the trial itself. Yet the herbage was very much more palatable than the winter grass experimented with in the December and January trials of the following winter, and no difficulty was experienced in securing consumption of a full ration. The relatively slight effect of frost on palatability in this case must be ascribed to the immature character of the herbage, which, as has already been noted, presented a short, leafy and lawn-like appearance. On the other hand, the herbage of the December and January trials of the following winter was in a considerably more advanced stage of growth, and in these cases the less severe frosts of this part of the 1932–3 winter were responsible for a very marked loss of palatability. It must be concluded, therefore, that both the visible effects of frost and the loss of palatability resulting from frost action are much less drastic with short, leafy grass than with grass in a more advanced stage of growth.

SUMMARY.

An attempt has been made in the investigation described in this paper to elucidate the nutritional characteristics of winter pasturage. The yield, composition and digestibility have been determined of pasturage produced by unrestricted growth over the following periods: (1) end of July 1932 to December 1932; (2) end of August 1932 to January 1933; (3) end of September 1932 to February 1933; (4) end of October 1931 to March 1932. In both years of experiment the winters were mild and open, and the conditions as a whole were such as to enable the nutritional possibilities of winter grazing to be studied under the most favourable conditions. In order to assess the influence of winter conditions on composition and feeding value the results in every case have been compared with data, obtained in investigations in previous years on the same pasture, for spring and summer herbage of comparable height, stage of growth and botanical composition.

The herbage produced from the end of July to December was essentially leafy in character, varying from 4 to 9 in. in height, with tufts of cocksfoot up to 12 in. Many of the grasses were brown tipped by frost action, the cocksfoot being most affected. Compared with spring grass of similar botanical characteristics, it was poorer in protein, lime and phosphoric acid, and richer in fibre and N-free extractives. Its digestibility and nutritive value were also poor by comparison with the spring herbage, the data suggesting that the winter grass, despite its leafy character, had undergone a considerable degree of lignification.

It is concluded that a leafy winter growth may closely resemble a spring growth in respect of mixture of grass species, height and stage of growth and yet be very definitely inferior in composition, digestibility and feeding value. Stage of growth is not the sole factor that determines composition and digestibility of pasture herbage; meteorological conditions, particularly in relation to their effect on the rate of growth, must also be taken into account. The inferior composition and nutritive value of the winter pasturage are held to be a consequence of the cessation of growth in the grasses as a result of cold and frost, this cessation being accompanied by physiological processes leading to a re-organisation of the material already in the plants as a means of defence against the inclement conditions. The changes thus brought about result in a partial lignification of the fibrous constituent and a consequent lowering of digestibility and feeding value, despite the fact that the grasses have not progressed further than the leafy stage. It is not surprising therefore that the effects produced by the cold of winter are in many respects similar to those brought about by severe drought in summer, the main distinction being that summer drought raises the lime content whereas winter frosts cause it to be depressed. The composition and digestibility of grass are to be related not only to the stage of growth at which the herbage has arrived, but also to the rate of growth as influenced by meteorological factors. The latter, however, have a predominant influence only in times of cold and frost (winter) or severe drought (summer).

The herbage investigated in the January trial was distinctly less advanced than that dealt with during December, since the growth period (end of August to January) had not included the month of August, at which period a small, secondary flush of growth on pastures is normally experienced. It was a leafy growth, 2–4 in. in height, with small areas up to 7 in. Its appearance suggested that the younger grasses are able to withstand the effects of frost more successfully than the same grasses at a more advanced stage of growth. Its protein content was higher than that of the December herbage, but again the winter herbage was found to compare unfavourably in respect of composition, digestibility and starch equivalent, with spring grass of similar height and stage of growth. It compared more favourably in these respects with drought-affected July grass grown on the same pasture in a previous season under a system of monthly cuts and resembling the winter herbage in height and stage of growth.

The February herbage was produced almost wholly under winter conditions (end of September to February) and was therefore not very advanced in growth, consisting of a short, leafy herbage from 1½ to 3 in.

in height. It was quite evident to the eye that this younger, shorter herbage was distinctly less affected by frost than the older, longer grass. The disparity in composition and digestibility between this winter herbage and the spring and summer herbage of similar external characteristics was distinctly less marked than was the case in the January and December trials. The improved fibre digestion coefficient pointed to a lesser degree of lignification, and this was accompanied by improvements in the digestibility of the other constituents in the herbage. This was not to be ascribed to the setting-in during February of more favourable meteorological conditions from the growth standpoint, but was rather to be explained on the assumption that the depressing influence of winter conditions on the composition and digestibility of pasture herbage is less pronounced with short, leafy herbage than with longer and more advanced grass.

Support for this hypothesis was forthcoming from the results that were obtained in the investigation of the herbage produced over the period from the end of October to the following March. Despite its long period of unrestricted development, this growth presented a lawn-like appearance, being wholly leafy in character and no more than 1½–2 in. in height. It displayed, in respect of composition, digestibility and starch equivalent, a very close approach to short, leafy pasturage produced during the normal pasture season. A twofold explanation is put forward to account for the very satisfactory composition and digestibility of this fourth growth of winter herbage: (1) Winter conditions cause a smaller deterioration in the composition and feeding value of short, leafy grass than is the case with a longer and more advanced leafy growth. (2) The improved composition and digestibility are possibly the earliest manifestation of the strong growth impulse that becomes evident to the eye during April in an abundance of new growth on the pasture. This impulse may be able to make itself felt during the first half of March and, although not as yet strong enough to occasion much actual growth of new tissue, is sufficient to awaken physiological activity within the plants and modify, in preparation for new growth, the chemical character of the plant tissues. The herbage plants in this process lose the partially-lignified character imposed on them by winter conditions and take on the non-lignified nature associated with spring.

In considering the yield data, it is pointed out that the weather in both the winters of experiment was more than usually favourable to the production of out-of-season growth. On the other hand, it is noted that the experimental pasture by no means belongs to the most highly productive type of grassland.

Although the herbage produced over the periods (1) end of September to February and (2) end of October to March displayed the best composition and feeding value, the yields of grass in both cases were too low to have any significance in farming practice. Indeed, it would appear necessary to discontinue the grazing of pastures at the end of July if it is desired to produce an adequate amount of herbage for grazing during the winter months, at any rate under such climatic conditions as obtain in East Anglia. Under these conditions the present pasture would have produced, for grazing in December, 1787 lb. of dry matter per acre, including 1009 lb. of starch equivalent and 174 lb. of digestible protein. This represents 87 days' keep for an 8 cwt. store bullock increasing in live-weight at the rate of 1 lb. per day.

An outstanding observation in these winter grass feeding trials is the discovery that, compared with spring or summer grass, the winter herbage had a definitely unpalatable character. It is found that frost, with its accompanying browning effect, is the most important factor leading to this reduction in palatability. Moreover, the effect is not simply proportional to the degree of severity of the frost, but is also related to the stage of growth of the herbage at the time. The conclusion is drawn that both the visible effects of frost and the loss of palatability resulting from frost action are much less drastic with short, leafy grass than with grass in a more advanced stage of growth.

In conclusion, the writers have pleasure in acknowledging their indebtedness to Dr R. E. Evans and Mr D. B. Norman for valuable assistance in various phases of the investigation, to Dr G. D. H. Bell for help in the carrying out of the botanical surveys of the pasture, and to Messrs V. Thurlbourn and C. Bendall, in whose experienced hands the care of the experimental animals was placed throughout the investigation.

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APPENDIX

Digestion Tables.

Growth period	Sheep XXI Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.	Sheep XXII Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.
(1) End of July 1932 to Dec. 1932:														
Daily ration	1084·40	827·94	140·65	24·94	465·75	196·60	256·46	1084·40	827·94	140·65	24·94	465·75	196·60	256·46
Food residues	267·90	75·65	13·66	2·79	42·46	16·74	192·25	310·70	111·17	19·57	4·32	58·10	29·18	199·53
Net consumption	816·50	752·29	126·99	22·15	423·29	179·86	64·21	773·70	716·77	121·08	20·62	407·65	167·42	56·93
Voided	328·29	248·44	51·69	17·12	100·96	78·67	79·85 *	293·65	212·34	41·50	13·76	95·21	61·87	81·31 *
Digested	488·21	503·85 *	75·30	5·03	322·33	101·19	—	480·05	504·43 *	79·58	6·86	312·44	105·55	—
Digestion coefficients (%)	59·79	66·97	59·30	22·71	76·15	56·26	—	62·05	70·37	65·72	33·27	76·64	63·04	—
(2) End of Aug. 1932 to Jan. 1933:														
Daily ration	875·20	628·74	138·63	25·82	319·01	145·28	246·46	875·20	628·74	138·63	25·82	319·01	145·28	246·46
Food residues	220·00	70·07	16·54	1·92	38·15	13·46	149·93	379·00	208·34	49·50	7·65	104·76	46·43	170·66
Net consumption	655·20	558·67	122·09	23·90	280·86	131·82	96·53	496·20	420·40	89·13	18·17	214·25	98·85	75·80
Voided	278·82	176·56	42·65	17·34	67·16	49·41	102·26 *	203·60	146·62	39·85	14·89	52·40	39·48	56·98
Digested	376·38	382·11 *	79·44	6·56	213·70	82·41	—	292·60	273·78	49·28	3·28	161·85	59·37	18·82
Digestion coefficients (%)	57·44	68·40	65·07	27·45	76·09	62·52	—	58·97	65·12	55·29 †	18·05	75·54	60·06	24·83
								Sheep XXIII						
(3) End of Sept. 1932 to Feb. 1933:														
Daily ration	1217·20	878·70	220·44	37·73	429·19	191·34	338·50	1220·80	881·29	221·09	37·84	430·45	191·91	339·51
Food residues	366·90	141·73	35·11	4·77	79·14	22·71	225·17	344·50	147·24	42·17	6·13	71·72	27·22	197·26
Net consumption	850·30	736·97	185·33	32·96	350·05	168·63	113·33	876·30	734·05	178·92	31·71	358·73	164·69	142·25
Voided	319·88	227·90	67·96	19·32	94·73	45·89	91·98	312·39	195·70	50·84	14·73	79·29	50·84	116·69
Digested	530·42	509·07	117·37	13·64	255·32	122·74	21·35	563·91	538·35	128·03	16·98	279·44	113·85	25·56
Digestion coefficients (%)	62·38	69·08	63·33 †	41·39	72·94	72·79	18·84	64·35	73·34	71·59	53·55	77·89	69·13	17·97
(4) End of Oct. 1931 to March 1932:	Sheep XIX							Sheep XX						
Daily ration	1739·50	1386·04	322·68	65·58	790·43	207·35	353·46	1735·40	1382·77	321·92	65·42	788·57	206·86	352·63
Food residues	184·40	38·70	9·01	1·83	22·07	5·79	145·70	130·10	25·10	5·84	1·19	14·31	3·76	105·00
Net consumption	1555·10	1347·34	313·67	63·75	768·36	201·56	207·76	1605·30	1357·67	316·08	64·23	774·26	203·10	247·63
Voided	530·44	310·95	89·69	27·92	145·68	47·66	219·49 *	562·25	316·69	89·06	30·32	148·34	48·97	245·56
Digested	1024·66	1036·39	223·98	35·83	622·68	153·90	—	1043·05	1040·98	227·02	33·91	625·92	154·13	2·07
Digestion coefficients (%)	65·89	76·92	71·41	56·20	81·04	76·35	—	64·98	76·67	71·82	52·79	80·84	75·89	—

* These anomalies arise from the difficulty of accurately sampling the food residues, which contained most of the soil included in the grass samples. They do not, however, detract significantly from the value of the digestion coefficients as a guide to the digestibility and nutritive value of the grass at this period of the year.

† These comparatively low protein digestion coefficients were due to the softness of the faeces from the sheep concerned. In these cases, the protein digestion coefficients for the duplicate animal, instead of the mean values for the two sheep, are used in the text. The agreement between the digestion coefficients from the duplicate sheep in one or two other instances is not so close as is usually obtained in this type of work, but this might be anticipated in trials where the food under test is of an unpalatable character. In the fourth trial, where the grass displayed its highest palatability, the results for the two sheep display the best degree of harmony.

THE LOSS OF ACTIVITY OF PYRETHRUM. II.

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(With Five Text-figures.)

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INTRODUCTION.

In a previous paper (8) of a preliminary nature it was shown that one way in which the pyrethrins lost their activity was by oxidation, particularly when exposed to light. In intense light the reaction was rapid when the pyrethrins were dispersed upon a fine inert powder so as to give a large surface area, while the incorporation of certain antioxidants tended to stabilise the pyrethrins. In the present paper the data there presented are amplified and certain corrections are made. An attempt is also made to ascertain the rate of loss of activity by exposure of dusts under more uniform conditions, to ascertain how far the acid method of estimating the pyrethrins will determine quantitatively the loss of activity under different conditions of exposure, and what degree of correlation exists between the chemical and the biological methods of evaluation used by us.

EXPERIMENTAL.

Exposure of pyrethrinised dusts to 1000-*watt lamp*. In the experiments previously described (*loc. cit.*), powdered pyrethrum flowers and pyrethrinised dusts were exposed to sunlight in a glasshouse. This procedure gave rise to daily variations in the amount of radiation received by the exposed samples, rendering impossible an accurate quantitative determination of the decline in activity with time. It was decided, therefore, to see how rapidly loss of toxicity would take place in pyrethrinised dusts under radiation from an artificial source of light, but not at this stage to attempt too accurate a control of the temperature. A 1000-watt tungsten filament lamp was used, together with a large white enamelled reflector, the optical contour of which was a combination of concave and cylindrical reflecting surfaces. The maximum intensity of light with even illumination was obtained in the zone of 0–45° and as far as possible the dusts were exposed within this area. The lamp operated at about 2900° K. and gave very little ultra-violet radiation. As the temperature varied from day to day, the exposure of samples to be compared was carried out in trays placed side by side at a distance of 2 ft. 3 in. from the lamp. Illumeter tests indicated the illumination at this distance to be approximately 1000 foot-candles.

The frequent stirring of the dusts was of importance, as the reaction in the presence of light was apparently a surface one. The stirring was done by hand, in the earlier experiments once every five hours, and in the later experiments every half-hour, the dusts being smoothed out as level as possible after each operation. It was found that with untreated pyrethrinised dusts the loss of activity proceeded with considerable rapidity.

In the first series of experiments, arranged to test the method, the dusts were prepared as follows: three portions of 5 gm. of a concentrated extract of pyrethrum were each dissolved in 25 c.c. of alcohol. One solution was added directly to 100 gm. of talc, and after taking off the alcohol *in vacuo* in the dark, the dried powder was finely sieved. To the other two solutions 5 gm. of hydroquinone and 5 gm. of tannic acid were added respectively, shaken till dissolved and each solution added to 100 gm. of fine talc and treated as before. Each dust contained 0·5 per cent. pyrethrin I. After thorough mixing two portions of 25 gm. of the untreated pyrethrinised dust were weighed out into flat-bottomed dishes, one of which was immediately covered with a lead sheet. 25 gm. of each of the dusts treated with antioxidant were also placed in similar dishes. The dusts were exposed to the light of a 1000-watt lamp, in an otherwise darkened room, stirring and levelling being carried out every five hours. The maximum surface temperatures varied, and in the open dishes ranged from 29 to 38° C. but was 2° C. lower in the lead-covered dish. A sample of the untreated pyrethrinised dust was kept in the dark in a cool cellar, to act as a control. It was observed that on exposure the surface yellow colour of the sample containing hydroquinone was retained with very little change, that the one containing tannic acid took on a greyish shade, whereas the colour of the uncovered untreated sample was completely discharged after a few hours. Little change was seen in the colour of the dust covered by the lead sheet. At the end of definite periods weighed quantities were taken from each dish and extracted with a known volume of alcohol. The alcoholic extracts were finally diluted with 0·5 per cent. solution of saponin in water, each dilution being brought up to the same concentration of alcohol, and sprayed upon *Aphis rumicis* in the apparatus and with the procedure previously described (9). The sprayings were carried out in triplicate at each concentration, using ten insects at a time. The results are given in Table I. The dilutions tested are expressed in terms of the content of pyrethrin I which they would have had before exposure.

The data set forth in Table I are the results of experiments carried out on three separate occasions. The effects of the sprays were judged 44 hours after their application. The data of the series *a*, *b*, *c* show that after an exposure of 42 hours the dust, shaded from the lamp by the lead sheet, is not significantly different in toxicity from the unexposed dust kept in the cellar. The sample without antioxidant shows marked degeneration after 10 hours, whereas the addition of the antioxidants, tannic acid and hydroquinone, have effected a measure of stabilisation. A slow decline in the activity of the dusts containing antioxidants does take place and the question arises, whether some of the loss of activity may not be due to reactions other than oxidation.

Antioxidants and accentuation of toxicity. In connection with the retardation of loss of activity by antioxidants one of us has previously suggested (8) that their addition to pyrethrum sprays might accentuate toxicity by preserving the activity of the pyrethrins after spraying. A carefully carried out experiment in which were compared the insecticidal values of pyrethrum extracts, with and without addition of the two antioxidants, tannic acid and hydroquinone, failed to confirm this possibility when the insects were kept in the dark after spraying. Three lots of 1·0 gm. of a concentrated extract of pyrethrum were dissolved in alcohol. To two, 1 gm. of hydroquinone and 1 gm. tannic acid were

Table I. *The effect of exposure to 1000-watt lamp upon pyrethrinised talc dusts, treated and not treated with antioxidants.*

Test subject, *Aphis rumicis*. M. & D. = moribund and dead, allowing for control.

			M. & D. % after 44 hours for dusts exposed			
Description	Concentrations tested. Pyrethrin I in original dust mg./1000 c.c.	No exposure M. & D. %	10 hours	22 hours	32 hours	42 hours
(*a*) Not treated with antioxidant. Not exposed	10	100	—	—	—	—
	5	100	—	—	—	—
	2·5	92	—	—	—	—
Not treated with antioxidant. Exposed under lead cover	10	—	100	100	100	100
	5	—	100	100	100	100
	2·5	—	96	88	100	100
Not treated with antioxidant. Exposed to 1000-watt lamp	30	—	—	—	—	6
	20	—	—	—	8	0
	15	—	—	40	10	8
	10	—	84	36	0	4
	5	—	88	0	8	—
	2·5	—	52	—	—	—
Control: saponin 0·5 gm./100 c.c., alcohol 6 c.c./100 c.c.		(16·6)				
(*b*) Treated with tannic acid 5 %	20	—	—	—	100	—
	10	—	—	100	100	—
	7·5	100	100	100	95	—
	5	100	100	89	87·5	—
	2·5	100	86	46·5	43	—
	1	55	45	—	—	—
Control: saponin 0·5 gm./100 c.c., alcohol 6 c.c./100 c.c.		(6·6)				
(*c*) Treated with hydroquinone 5 %	20	—	—	—	—	100
	15	—	—	—	100	—
	10	—	—	100	100	86
	7·5	96	100	100	74	76
	5	92	88	88	53	50
	2·5	24	66	60	16	—
	1	14	40	—	—	—
Control: saponin 0·5 gm./100 c.c., alcohol 6 c.c./100 c.c.		(16·6)				

added respectively. The solutions were made up to 50 c.c. and, after dilution to the concentrations given in Table II, were tested in the usual way. Each dilution contained 0·5 gm. of saponin and 0·5 c.c. of alcohol per 100 c.c. of spray fluid. The figures given in Table II are the results of sprayings in fivefold replication, the standard error of the mean percentage of moribund and dead insects for each concentration being also given.

The data indicate that there is very little difference in the activity of the three preparations. At the concentration 4 mg. per 1000 c.c. pyrethrin I there is a fairly large discrepancy between the values for the preparations using tannic acid and hydroquinone, but an analysis of the data shows that this difference between the values is not significant. From these figures it is also safe to assume that the differences found between the toxicities of the samples in Table I are not due to any accentuation of toxicity owing to the addition of the antioxidants.

Table II. *The effect of antioxidants on the toxicity of pyrethrum extracts.*

Insect used, *Aphis rumicis*. Fivefold replication, 10 insects at a time.
Original solutions contained 0·02 gm./100 c.c. pyrethrin I. Antioxidants 2 gm./100 c.c.

Test	Concentration in pyrethrin I mg./1000 c.c.	Moribund and dead % 36 hours after spraying	Standard error %	Moribund and dead % allowing for control
Control: saponin 0·5 gm./100 c.c., alcohol 0·5 c.c./100 c.c.	—	16	±6·0	0
Pyrethrum extract untreated	10	100	—	100
	8	100	—	100
	6	100	—	100
	4	90	±4·47	88
	2	51	±5·83	41·7
Control: as above but with 0·01 gm./100 c.c. tannic acid	—	12	±5·45	0
Pyrethrum extract + tannic acid	10	100	—	100
	8	98	±2·0	97·7
	6	98	±2·0	97·7
	4	92	±2·0	91
	2	48	±2·0	41
Control: as above but with 0·01 gm./100 c.c. hydroquinone	—	4	±2·45	0
Pyrethrum extract + hydroquinone	10	100	—	100
	8	96	±2·45	96
	6	94	±6·0	94
	4	80	±6·32	79
	2	44	±5·0	41·7

THE EXTENT TO WHICH THE ACID METHOD WILL TRACE OUT LOSS OF ACTIVITY.

Experiments with pyrethrinised dusts. In an earlier paper (8) the loss of activity of pyrethrum, in a powdered form, and of pyrethrinised dusts was followed by exposing them to sunlight and periodically carrying out biological tests upon bean or wheat aphis. The objections to this method are due to difficulties and inaccuracies inherent in biological trials, chiefly owing to the fact that the operator has no assurance that the resistance of the insects to the action of the poison does not change with varying meteorological conditions. The results of tests carried out at different times might not be strictly comparable. A chemical method does not suffer from this disadvantage. Tests can be carried out on samples after prolonged exposure, and comparisons made with the original sample. This is a matter of some importance as it is known that pyrethrum may suffer slow degeneration when carefully stored in the dark, as indicated by Gnadinger and Corl (5). Before, however, attempting to employ a chemical method, it is imperative to ascertain to what extent a correlation can be obtained between the chemical and biological examinations. In other published papers we have indicated that, in general, the determination of pyrethrin I by the acid method has placed samples in their correct order of toxicity. Our present problem is a more difficult one, as a systematic error inherent in the analytical method, although small in the case of a dust rich in pyrethrins, may have a proportionately greater significance as the activity declines on exposure.

Two samples of pyrethrinised talc dusts, one relatively rich and the other poor in pyrethrin content, were prepared by extracting known quantities of powdered pyrethrum with petroleum ether and incorporating the extract with finely powdered talc, evaporating off the petroleum ether *in vacuo* and finally sieving (100 mesh to the inch). The operations were carried out in the dark and the prepared dusts stored in a cool cellar. Just before exposure the samples were analysed by the acid method (10) with the introduction of one modification. The water-soluble pyrethrin II acid was extracted with three successive portions, of 50 c.c. each, of sodium-treated ether in a separating funnel, each ether extract being washed with a little distilled water. Portions of 20 gm. of the samples were spread evenly in a thin layer in circular trays of the same diameter and exposed in symmetrically disposed positions under a 1000-watt lamp, the distance from the lamp being the same in each case. Every half-hour the samples were stirred and again evenly spread. The samples were taken off at the end of the 2, 4, 8, 12, 16 and 60 hours' exposure in the case of the poor dust, and at the end of 4, 8, 12, 16, 20 and 50 hours' exposure in the case of the rich dust. An aliquot part of each was analysed and the remainder of the sample stored for a short time in a closed container in a cool cellar and used for biological tests. The results of the analyses are given both in tabular and graphical form later in this paper (Table VII, Fig. 3).

In the majority of the biological trials, for each concentration tested, fifty insects were used, and these were selected from the adult apterous females in order to obviate difficulties arising from ecdysis in modifying resistance.

In general, only two or at the most three samples were tested on the same day and strict comparisons made only for those samples, but a preliminary series of tests was carried out on five samples of the poorer dusts which included the unexposed, and those exposed 4, 8, 12 and 16 hours. The tests were only made in duplicate and therefore strictly quantitative deductions cannot be drawn as to the relative activities of the samples. The relevant data are given in Table III.

Table III. *Toxicity of extracts prepared from dusts before and after exposure to* 1000-*watt lamp.*

Insect used, *Aphis rumicis*. Tests in duplicate, 10 insects at a time. Examination 2–3 days after spraying. M. & D. = moribund and dead insects.

	Concentrations mg./1000 c.c. tested in terms of				
Description of test	Pyrethrin I before exposure	Total pyrethrins before exposure	Pyrethrin I after exposure	Total pyrethrins after exposure	M. & D. %
Pyrethrinised talc dust	11	24	—	—	100
Not exposed	9	19	—	—	80–100
Analysis:	7	14	—	—	80–100
pyrethrin I 0·26 %	4·5	9·5	—	—	52–62
pyrethrin II 0·29 %	2	5	—	—	10–35
Exposed 4 hours	34	72	29	64	100
Analysis:	27	57	23	50	100
pyrethrin I 0·22 %	18	38	15	34	77–85
pyrethrin II 0·27 %	14	29	11	25	75–90
	9	19	7·5	17	45–57
	4·5	9·5	4	8	21–42
Exposed 8 hours	90	90	18	110	100
Analysis:	70	145	13	83	100
pyrethrin I 0·05 %	45	95	8·7	56	100
pyrethrin II 0·27 %	35	70	6·5	41	82
	20	50	4	25	67–71
	10	24	2	12	15–35
Exposed 12 hours	680	1440	60	610	100
Analysis:	450	950	40	405	100
pyrethrin I 0·024 %	220	470	20	200	100
pyrethrin II 0·22 %	110	240	10	100	72–95
	56	120	5	50	40–70
	23	50	2	20	21–26
Exposed 16 hours	1360	2860	104	985	100
Analysis:	900	1900	70	665	100
pyrethrin I 0·02 %	680	1440	50	470	100
pyrethrin II 0·17 %	450	950	35	330	80–95
	230	480	17	165	50–65
Control:					2·5–17·5
0·5 gm./100 c.c. saponin					
and 5·0 c.c./100 c.c. alcohol					

The figures in the table show that although toxicity rapidly falls off after the 4-hour period, some activity persists after 16 hours' exposure, but the toxicity is apparently not commensurate with the small residual value of matter expressed as pyrethrin I (0·02 per cent.) which is probably extraneous matter. On the whole, as far as one can judge from these data, the estimation of pyrethrin I traces out the loss of activity better than the figures expressed as total pyrethrins, but some correction for an error in the estimation of pyrethrin I is required. As in this series too few insects were used for the employment of statistical analysis, a second series of insecticidal tests was carried out in fivefold replication, in which the samples of unexposed dust and those exposed to a 1000-watt lamp for 8 and 16 hours were used. The subsequent operations were carried out as far as possible in the dark. After extraction with petroleum ether in the dark the solvent was taken off in a stream of carbon dioxide and finally *in vacuo*, the residue was extracted, with cooling, with five lots of methyl alcohol, which was finally taken off *in vacuo*, and the residue dissolved in a small amount of absolute alcohol and made up to a known volume with 0·5 per cent. saponin solution. The alcohol content for each dilution was adjusted to 5 c.c. per 100 c.c. of solution. The insects were sprayed in a modification of the apparatus previously employed, an account of which will be subsequently published. Owing to the difficulty encountered in keeping the foliage, near which the insects were placed, fresh in petri dishes during the hot dry weather, the insects after spraying were placed without handling in tubes afterwards covered by muslin and kept in a cool cellar. Examination of the insects was made 20 and again 44 hours after spraying. The data are set out in Table IV and expressed graphically in Fig. 1, section A.

Table IV. *Insecticidal tests with pyrethrinised talc dusts exposed for different periods to* 1000-*watt lamp.*

Insect used, *Aphis rumicis*. Tests in fivefold replication, 10 insects at a time. Results 44 hours after spraying. The dust exposed was poor in pyrethrin content. M. & D. = moribund and dead.

	Concentrations mg./1000 c.c., tested, in terms of								
Description	Pyrethrin I as found	Pyrethrin II as found	Total pyrethrins as found	Pyrethrin I adjusted	Total pyrethrins with adjusted pyrethrin I	M. & D. after 44 hours %	Standard error %	M. & D. allowing for control %	Probits (Bliss)
Unexposed	11·3	12·5	24	10	22·5	100	—	100	—
Analysis:	9	10	19	8·3	18	100	—	100	—
pyrethrin I 0·26 %	6·8	7·5	14	6·3	14	100	—	100	7·722
pyrethrin II 0·27 %	4·5	5	9·5	4·2	9	92	±3·7	91·8	6·392
pyrethrin I after deducting	2·3	2·5	5	2·1	4·5	40	±4·47	38·8	4·715
0·02 % = 0·24 %	1·1	1·2	2	1	2	4	±2·4	2·04	2·954
Exposed 8 hours	7·2	35	42	4·6	39·5	78?	±9·7	77·5?	—
Analysis:	6·0	29	35	3·6	32·5	76	±9·3	75·5	5·690
pyrethrin I 0·055 %	4·8	23	28	3·05	26	68	±6·6	67·3	5·448
pyrethrin II 0·25 %	4·2	20·5	24·5	2·65	23	58	±8·0	57·1	5·179
pyrethrin I after deducting	3·6	17·5	21	2·3	20	55	±5·0	54·0	5·100
0·02 % = 0·035 %	3·0	14·5	17·5	1·9	16·5	38	±3·7	36·7	4·660
	2·4	11·5	14	1·5	13	8	±4·9	6·1	3·454
Exposed 16 hours	35	280	315	—	—	92·8	±3·7	92·6	—
Analysis:	26	210	236	—	—	70	±7·0	69·4	—
pyrethrin I 0·02 %	17	140	157	—	—	70·4	±7·3	69·8	—
pyrethrin II 0·16 %	8·7	70	79	—	—	34	±4·0	32·6	—
pyrethrin I after deducting	4·3	35	39	—	—	4	±3·0	2·04	—
0·02 % = nil									
Control:						2			
saponin 0·5 gm./100 c.c.									
+ alcohol 5 c.c./100 c.c.									

The figures for pyrethrin I and II, found by the determination of the volatile and water-soluble acids, are shown in columns 2 and 3 of the table. The amount of pyrethrin I steadily declined, the value for the sample exposed 16 hours being very small, whereas the pyrethrin II value after 16 hours' exposure is still appreciable in amount. An examination of the corresponding toxicities of the three samples shows that the toxicity values for the sample exposed 16 hours are not com-

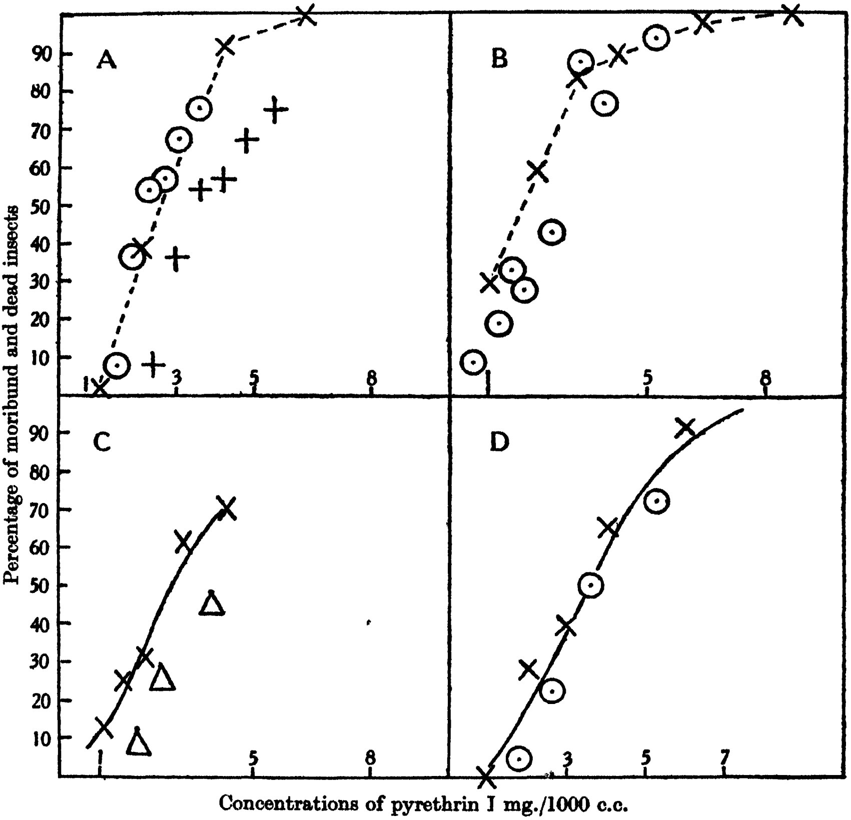

Fig. 1. Relation between concentration of pyrethrin I and toxicity. Pyrethrinised dusts exposed for different periods.

Section A. Poor dust.
× Unexposed (corrected).
⊙ Exposed 8 hours (corrected).
+ Exposed 8 hours (uncorrected).

Section B. Rich dust.
× Unexposed (corrected).
⊙ Exposed 8 hours (corrected).

Section C. Rich dust.
× Unexposed (corrected).
△ Exposed 6 hours (corrected).

Section D.
× Harpenden flowers 1932 (corrected).
⊙ Dalmatian flowers No. 1606 (corrected).

mensurate with even the small residual value expressed as pyrethrin I, and the conclusion is drawn that the residue of 0·02 per cent. is probably non-pyrethrin matter. We have, therefore, felt justified in deducting this amount from the values of the other two samples, so that the figures in column 5 representing the concentrations tested in the case of the samples labelled "unexposed" and "exposed 8 hours" are corrected for this residue. A comparison between columns 2 and 5 will show that the correction in the case of the unexposed samples has but a small effect upon the concentrations tested, but that in the case of the sample exposed 8 hours it is of greater significance. The percentages of moribund and dead insects in columns 7 and 9, for the sample exposed 8 hours, are in much closer agreement with those given by the unexposed samples when the adjusted figures are taken.

In section A of Fig. 1 the results corrected for an error of 0·02 per cent. pyrethrin I are plotted, but the uncorrected values are also shown (by points marked +). It is obvious that in the latter case there is a departure from coincidence.

Two further series of tests were carried out on a talc dust rich in pyrethrins, the results of which are given in the series A and B of Table V.

In series A of Table V, the data afford a comparison for three samples: (1) the unexposed, (2) exposed 8 hours, (3) exposed 16 hours. An exposure of 8 hours has led to a big reduction in the amount of pyrethrin I and a further exposure of 8 hours has led to a further reduction to 0·044 per cent. Known quantities of exposed and non-exposed samples were extracted and diluted as previously described. The spray tests were carried out in fivefold replication and the percentage number of moribund and dead insects determined after about 20 and again after 44 hours. The values obtained after the latter interval are expressed in the table, both with and without a correction for the control sprays, for which a saponin and alcohol solution of the same strength as that used in the dilutions was tested. The data given indicate that the dilutions from the extract of the sample exposed 16 hours do not give results commensurate with the small residue (0·044 per cent.) expressed as pyrethrin I, and the conclusion is drawn, as in the previous case, that the residue is non-pyrethrin material, and that its deduction from the values found for the samples, unexposed and exposed 8 hours, would probably give a better evaluation of those samples. The corrected values for pyrethrin I are given in column 5. The concentrations thus corrected are plotted against the percentage number of moribund and dead insects in Fig. 1, section B.

Table V. *Insecticide tests with pyrethrinised talc dusts exposed for different periods to 1000-watt lamp.*

Insect used, *Aphis rumicis*. Tests in fivefold replication, 10 insects at a time. Results 44 hours after spraying. The dust exposed was rich in pyrethrins. M. & D. = moribund and dead.

Description	Concentrations mg./1000 c.c., tested, in terms of								
	Pyrethrin I as found	Pyrethrin II as found	Total pyrethrins as found	Pyrethrin I adjusted	Total pyrethrins with adjusted pyrethrin I	M. & D. after 44 hours %	Standard error %	M. & D. allowing for control %	Probits (Bliss)
*Series A**									
Unexposed	9·1	8·3	17·4	8·6	16·9	100	—	100	7·854
Analysis:	6·9	6·2	13·1	6·4	12·6	98	±2	97·8	7·015
pyrethrin I 0·698 %	4·6	4·1	8·7	4·2	8·3	90	±1	89·3	6·243
pyrethrin II 0·63 %	3·4	3·0	6·4	3·2	6·2	84·4	±1·1	83·4	5·970
pyrethrin I after deducting	2·3	2·1	4·4	2·2	4·3	61·2	±1·4	58·6	5·217
0·04 % = 0·66 %	1·1	1·0	2·1	1·0	2·0	34	±5·1	29·6	4·464†
Exposed 8 hours	7·9	23·0	31	5·2	28	94	±4	93·6	6·522
Analysis:	5·9	17·0	23	3·9	21	78	±5·8	76·5	5·723
pyrethrin I 0·12 %	4·9	14·0	19	3·3	17	88	±5·8	87·2	6·136
pyrethrin II 0·34 %	3·9	11·0	15	2·6	13·6	46?	±11·7	42·4?	4·808†
pyrethrin I after deducting	2·9	8·5	11	1·9	10	32	±5·8	27·5	4·402
0·04 % = 0·08 %	2·46	7·0	9·5	1·6	8·6	37·2	±6·6	33	4·500
	1·96	5·7	8	1·3	7·3	24	±4	18·9	4·118
	1·0	3·0	4	0·65	3·6	14·3	±5·1	8·6	3·634†
Exposed 16 hours	28·6	157	186	—	—	82·3	±7·4	81·1	—
Analysis:	21·6	118	140	—	—	80	±4·5	78·7	—
pyrethrin I 0·044 %	14·4	78	92	—	—	66·6‡	±9·4	64·4	—
pyrethrin II 0·23 %	7·0	39	46	—	—	52	±3·7	48·8	—
pyrethrin I after deducting	3·5	19	23	—	—	23·4‡	±8·8	18·3	—
0·04 % = 0 %									
Control:						6·25	±6		
saponin 0·5 gm./100 c.c.									
+ alcohol 5 c.c./100 c.c.									
*Series B**									
Unexposed	4·6	4·1	8·7	4·3	8·4	72	±10·7	70·8	5·548
Analysis:	3·4	3·0	6·4	3·2	6·2	63·2	±7·0	61·6	5·295
pyrethrin I 0·698 %	2·3	2·1	4·4	2·2	4·3	34	±6·0	31·2	4·510
pyrethrin II 0·63 %	1·7	1·5	3·2	1·6	3·1	28	±5·8	25	4·325†
pyrethrin I after deducting	1·1	1·0	2·1	1·07	2·1	16·6	±5·3	13·1	3·878†
0·04 % = 0·66 %									
Exposed 6 hours	4·9	11·4	16	3·9	15	50	±7·1	47·9	4·947
Analysis:	3·3	7·7	11	2·6	10	32	±8·7	29·2	4·452
pyrethrin I 0·2 %	2·5	5·8	8	2·0	8	16	±7·5	12·5	3·850
pyrethrin II 0·46 %	1·6	3·8	5	1·3	5	4	±2·45	0	—
pyrethrin I after deducting	0·8	1·4	2	0·65	2	4	±2·45	0	—
0·04 % = 0·16 %									
Controls:						4·2	±4·0		
saponin 0·5 gm./100 c.c.						4·0	±2·45		
+ alcohol 5 c.c./100 c.c.									

* Results in series A and B cannot be strictly compared as the tests were carried out on separate days.

† Omitted in calculating regression line.

‡ Tests in triplicate.

Section B of Table V gives the insecticidal results for the samples unexposed and exposed 6 hours. An attempt was made to explore the region of the 50 per cent. mortality, but the data obtained were not complete, as with the sample exposed 6 hours the two lowest concentrations gave results not differing from those given by the controls, and the mortalities did not extend above the 50 per cent. death point.

Again an allowance of 0·04 per cent. in the estimation of pyrethrin I gave the closer correlation between concentration and effect. In Fig. 1, section C, this corrected concentration is plotted against percentage number of moribund and dead insects.

It was not expected that the estimation of pyrethrin I would evaluate completely the samples throughout the whole range of activity during exposure. In addition to the part played by non-pyrethrin compounds, the action of pyrethrin II is bound to have some effect, and it is a matter for some regret that our data cannot be regarded as demonstrating its extent. We are not satisfied that the acid method will show up the loss of pyrethrin II with precision, and we consider further work will be required on this point. The investigations outlined in the foregoing section indicate that, with a correction which is probably only just outside experimental error, the determination of pyrethrin I in the case of normal samples enables us to follow approximately the loss of activity.

Comparison between two samples of pyrethrum. In order to compare the results given by the acid method of analysis with those of biological trials, flowers grown in Harpenden and rich in pyrethrins and a Dalmatian sample poor in pyrethrins were analysed. The Harpenden sample was of the previous year's crop, whereas the Dalmatian sample was probably some years old. After the analysis, known amounts of each were extracted and diluted as before. Dilutions were made with 0·5 per cent. saponin and brought up to the same percentage content of alcohol. The results are given in Table VI.

It was found that the Harpenden sample after prolonged exposure gave a residual value of 0·036 per cent. of apparent pyrethrin I. A value of 0·04 per cent. was deducted from the estimates of pyrethrin I and the dilutions, adjusted for this value, are expressed in column 5. Corrected concentrations are plotted against the percentage number of moribund and dead insects in section D of Fig. 1.

It may be pointed out that the values of the concentrations of the extracts adjusted for an error of 0·04 per cent. gave results in closer agreement than the uncorrected values, and it is obvious that in Fig. 1, section D, one curve could be drawn which would fit both sets of data quite closely.

Statistical comparison of results. The statistical comparison of different experimental series relating the kill of aphides to the concentration of the pyrethrins is not an easy matter, since curves of this type commonly

Table VI. *Insecticide tests with two samples of pyrethrum, Harpenden* 1932 *crop and Dalmatian No.* 1606.

Insect used, *Aphis rumicis*. Tests in fivefold replication, 10 insects at a time. Results 44 hours after spraying. M. & D. = moribund and dead.

	Concentrations mg./1000 c.c., tested, in terms of								
Description	Pyrethrin I as found	Pyrethrin II as found	Total pyrethrins as found	Pyrethrin I adjusted	Total pyrethrins with adjusted pyrethrin I	M. & D. after 44 hours %	Standard error %	M. & D. allowing for control %	Probits (Bliss)
Harpenden	6·4	7·2	13·6	6·0	13·2	92	±5·8	91·3	6·360
Analysis:	4·3	4·8	9·1	4·0	8·8	68	±7·3	65·2	5·391
pyrethrin I 0·63 %	3·2	3·6	6·8	3·0	6·6	44·9	±4·4	40·1	4·749
pyrethrin II 0·71 %	2·1	2·4	4·5	2·0	4·4	34	±3·6	28·3	4·426*
pyrethrin I after deducting 0·04 % = 0·59 %	1·1	1·2	2·3	1·0	2·2	8	±3·7	0	
Dalmatian 1606	6·7	8·8	15·5	5·3	14·0	74	±6·0	71·7	5·574
Analysis:	4·5	5·9	10·4	3·5	9·4	54	±6·0	50	5·000
pyrethrin I 0·19 %	3·35	4·4	7·7	2·65	7·0	28·5	±3·9	22·3	4·238
pyrethrin II 0·25 %	2·2	2·9	5·1	1·76	4·7	12	±2·0	4·3	3·283
pyrethrin I after deducting 0·04 % = 0·15 %	1·1	1·5	2·6	0·88	2·4	2	±2·0	—	
Control: saponin 0·5 gm./100 c.c. + alcohol 5 c.c./100 c.c.						8	±2·0		

* Omitted in calculating regression line.

are sigmoid in character. Recently, however, it has been shown by Hemmingsen (6) and Gaddum (3) and by Bliss (1), working with different organisms and poisons, that if the dosage is expressed in logarithms, the resulting sigmoid curves are symmetrical, may be identified as cumulative normal frequency distributions, representing the variation between individuals in their susceptibility to the toxic agent, and can be transformed to straight lines. Their method is based on the following reasoning. Assuming that the minimum lethal dose of a poison is an index to susceptibility, if this could be determined exactly for each individual, the distribution of the number of individuals having each degree of susceptibility might be expected to follow the normal curve of error, which has been found to hold so widely elsewhere in biology. Actually, any given concentration, applied to a random sample of organisms, will kill not only those individuals requiring this particular minimum lethal dose but also all more susceptible individuals, so that instead of a differential curve of distribution, a series of concentrations will give an S-shaped cumulative or integral curve. In this curve each percentage kill corresponds to the area under the differential curve from the dosage (susceptibility) giving the smallest lethal effect up to a perpendicular erected at the dosage actually administered. By means of tables of the normal curve the expected dosage (susceptibility) expressed in units of the standard deviation may be read directly from the area represented by each percentage kill. If this "expected" dosage is plotted against the logarithm of the administered dosage the points will fall into a straight line. By means of this transformation to a straight line the relation between mortality and dosage can be computed for any given series within known limits of accuracy and the agreement or disagreement of two or more series determined. Our procedure has been to show, first, whether these dosage-mortality curves, transformed as above, differed significantly from parallelism and, secondly, whether they differed significantly from coincidence.

In carrying out the insecticidal tests, we attempted to explore the neighbourhood of the concentrations giving 50 per cent. moribund and dead, as we believe that here the most accurate comparisons can be made. We were not entirely successful. McCallan and Wilcoxon (7), who have examined the form of the toxicity surfaces for copper sulphate and sulphur, state that the 50 per cent. mortality point may not be the most accurate for purposes of comparison; nevertheless, the extremes of the curve should be avoided, and this seems to be a conclusion common to many investigators. The advantage derived from the use of the device outlined above is that one is enabled by its means to utilise a large range of data. We originally tested our data by means of Bliss's probits as first published (1), but as this list has been discarded the probits from this table are not tabulated. We have finally used his more recent table which he most kindly placed at our disposal in manuscript. In the latter case the method of weighting, worked out by him and Prof. R. A. Fisher (shortly to be published), has been used. In order to incorporate tests giving no survivors the correction recently determined by Bliss and Fisher has also been used. We have found that the lowest concentrations, when the tests were least accurate, frequently gave values departing from the general trend of the results. This has been noted in many quantitative biological evaluations of this type. Such values have been neglected and occasionally we have discarded a value which from the nature of the data has been open to suspicion of grave inaccuracies; *e.g.* two values marked ? in Tables IV and V have been neglected, as there was good reason for considering that they had been seriously influenced by the imperfect sampling of the insect population. Our procedure was to plot the probit values against the logarithms of the concentrations of pyrethrin I (corrected and uncorrected) and total pyrethrins for the various sets of data in Tables IV, V, VI. The figures for the following experiments were graphed: (1) poor dust not exposed and exposed 8 hours, (2) rich dust not exposed and exposed 8 hours, (3) rich dust not exposed and exposed 6 hours, (4) two unexposed samples of Harpenden and Dalmatian pyrethrum powder. It was observed that the corrected pyrethrin I values gave regression lines much nearer to coincidence for each of the above pairs of tests than the uncorrected pyrethrin I values or the estimations of total pyrethrins. It was, therefore, decided to ascertain the degree of concordance in the parallelism and in the coincidence of each pair of regression lines by Bliss's method. The constants of the regression lines of probits upon the logarithms of the concentrations, corrected for the residue of apparently non-pyrethrin matter, were determined, for each pair of the above tests, from the equation $Y = a + b\,(x - \bar{x})$. The determination of χ^2 for each line determined the goodness of fit. From the data so obtained the lines were tested for departure from parallelism and departure from coincidence by the χ^2 test as given by Bliss and by the table of "*t*" (2). The formulae used for the χ^2 tests were

$$\chi_b{}^2 = \frac{(b_1 - b_{11})^2}{\dfrac{1}{[\Sigma\,(wx^2) - \bar{x}\Sigma wx]_1} + \dfrac{1}{[\Sigma\,(wx^2) - \bar{x}\Sigma wx]_{11}}},$$

$$\chi_a{}^2 = \frac{[(a_1 - a_{11}) - b_c\,(\bar{x}_1 - \bar{x}_{11})]^2}{\dfrac{1}{\Sigma w_1} + \dfrac{1}{\Sigma w_{11}}}.$$

b_c, the mean slope of the two lines, is given by

$$b_c = \frac{[\Sigma wxy - \bar{x}\Sigma wy]_1 + [\Sigma wxy - \bar{x}\Sigma wy]_{11}}{[\Sigma\,(wx^2) - \bar{x}\Sigma wx]_1 + [\Sigma(wx^2) - \bar{x}\Sigma wx]_{11}},$$

where w is the weighting factor, the subscripts $_1$, $_{11}$ indicate one or other of the regression lines being compared, $\bar{x}$ is the mean value of x (logs of concentrations), y are probits.

The use of table of "*t*" involved the calculation of

$$t_a = \frac{(a_1 - a_{11}) - b_c\,(\bar{x}_1 - \bar{x}_{11})}{\sqrt{s_{a_1}{}^2 + s_{a_{11}}{}^2}},$$

$$t_b = \frac{b_1 - b_{11}}{\sqrt{s_{b_1}{}^2 + s_{b_{11}}{}^2}},$$

where a_1, a_{11}, b_1, b_{11} are the constants of the regression lines, s_{a_1}, $s_{a_{11}}$ are the standard errors of the a values of the two series given by

$$s_{a_1} = \sqrt{\frac{\chi_1{}^2}{n_1 \Sigma w_1}}, \quad s_{a_{11}} = \sqrt{\frac{\chi_{11}{}^2}{n_{11} \Sigma w_{11}}},$$

$s_{b_{\mathrm{I}}}$, $s_{b_{\mathrm{II}}}$ are the standard errors of the b values of the two series, given by

$$s_{b_{\mathrm{I}}}=\sqrt{\frac{\chi_{\mathrm{I}}^2}{n_{\mathrm{I}}\left[\Sigma\left(wx^2\right)-\bar{x}\Sigma wx\right]_{\mathrm{I}}}},\quad s_{b_{\mathrm{II}}}=\sqrt{\frac{\chi_{\mathrm{II}}^2}{n_{\mathrm{II}}\left[\Sigma\left(wx^2\right)-\bar{x}\Sigma wx\right]_{\mathrm{II}}}},$$

the other symbols having the same significance as for the χ^2 test.

The χ^2 table was entered at $n=1$ and the table of "t" at $n=$ the numbers of degrees of freedom.

The calculated weighted regression lines for the four series are plotted in Fig. 2. As a result of the statistical examinations the following conclusions were drawn:

Data of Table IV, Fig. 2, section A.

$\chi_b^2=0{\cdot}246$, $\chi_a^2=0{\cdot}484$, $t_b=0{\cdot}509$, $t_a=0{\cdot}946$.

Regression lines for unexposed and exposed samples do not depart significantly from parallelism or coincidence.

Data of Table V, series A, Fig. 2, section B.

$\chi_b^2=0{\cdot}047$, $\chi_a^2=2{\cdot}561$, $t_b=0{\cdot}272$, $t_a=1{\cdot}567$.

Regression lines for unexposed and exposed samples do not depart significantly from parallelism or coincidence.

Data of Table V, series B, Fig. 2, section C.

$\chi_b^2=0{\cdot}001$, $\chi_a^2=10{\cdot}009$, $t_b=0{\cdot}122$, $t_a=4{\cdot}344$.

Lines show a significant non-departure from parallelism but show a significant departure from coincidence by the χ^2 test. Departure from coincidence by the "t" test just significant[1].

Data of Table VI, Fig. 2, section D.

$\chi_b^2=0{\cdot}210$, $\chi_a^2=3{\cdot}250$, $t_b=1{\cdot}042$, $t_a=3{\cdot}418$.

Regression lines for Harpenden and Dalmatian flowers do not depart significantly from parallelism or coincidence.

It was noted in carrying out these tests that, in the first two series (Fig. 2, sections A and B) where the activity has fallen to a low level in the exposed samples, the points were more irregularly distributed about the regression lines than for the unexposed samples and that in general the regression lines for the exposed samples were slightly below those of the unexposed samples. The irregularity shown by the exposed samples may be due to the fact that, in order to obtain concentrations of pyrethrin I equivalent to those of the unexposed samples, much larger amounts of the dust had to be extracted, introducing a much higher proportion of non-pyrethrin material into the spray fluids. Thus, although the content of pyrethrin I in the whole spray fluid might be the same for equivalent dilutions for both the exposed and unexposed samples, the dilution in the dispersed phase would be greater in the case of the exposed sample. We know of no exact information on the influence of such disperse phase dilution, but it might well be important and render more difficult an

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[1] Similar results were obtained on statistical examination of the whole of the data taking the results of the spraying of each batch of ten insects separately. The departure from coincidence may be due to the fact that the sample was taken when loss of activity was proceeding at a rapid rate.

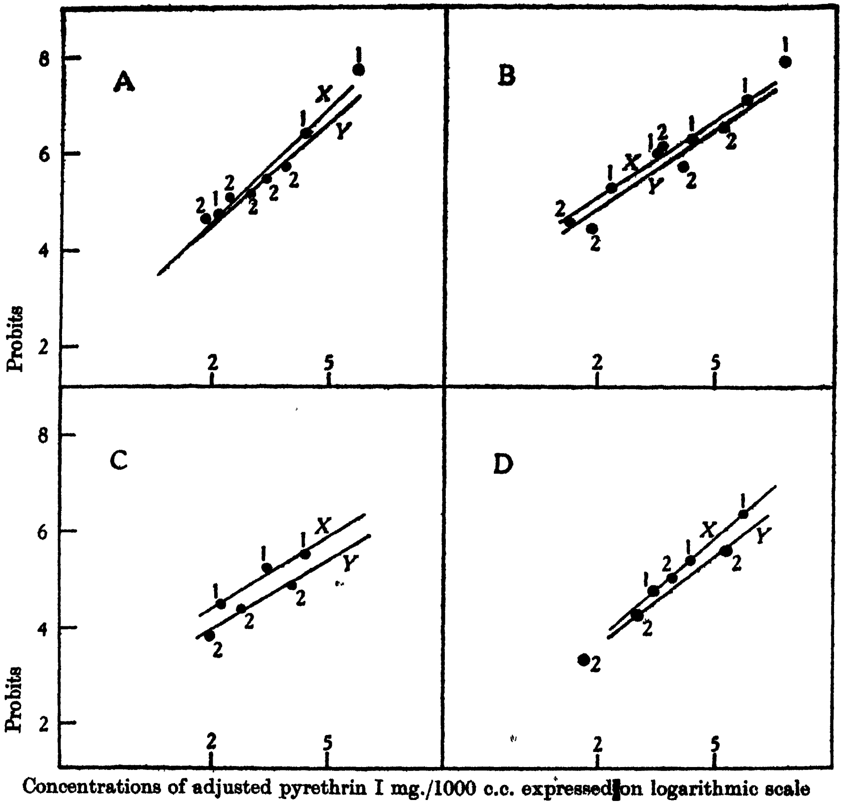

Fig. 2.

Section A. Poor dust (data Table IV).
X Unexposed ● 1
Y Exposed 8 hours ● 2

Section C. Rich dust (Table V, series B).
X Unexposed ● 1
Y Exposed 6 hours ● 2

Section B. Rich dust (Table V, series A).
X Unexposed ● 1
Y Exposed 8 hours ● 2

Section D. Data Table VI.
X Harpenden 1932 flowers ● 1
Y Dalmatian 1606 flowers ● 2

exact comparison of our samples. The conclusion that we feel entitled to draw from the above analysis is, that the estimation of the volatile acid expressed in terms of pyrethrin I and corrected for a small residual value will enable us to trace out loss of activity with approximate accuracy.

Chemical evaluation of loss of activity. Table VII gives the analytical data for the change in composition of the pyrethrinised dusts used in the biological trials on exposure to a 1000-watt lamp. The results are expressed graphically in Fig. 3.

Table VII. *Analysis of dusts exposed for different periods to* 1000-*watt lamp.*

Dusts spread in thin layers, and stirred every half hour.

		Exposure periods in hours					
	Not exposed	4	6	8	12	16	Over 50
Low quality dust:							
Pyrethrin I %	0·26	0·22	—	0·06	0·03	0·02	0·02
,, corrected	0·24	0·20	—	0·04	0·01	Nil	Nil
Pyrethrin II %	0·27	0·25	—	0·25	0·21	0·16	0·12
High quality dust:							
Pyrethrin I %	0·70	0·65	0·20	0·12	0·05	0·04	0·03
,, corrected	0·66	0·61	0·16	0·08	0·01	Nil	Nil
Pyrethrin II %	0·63	0·53	0·46	0·34	0·20	0·23	0·15

The data show that there is a definite lag period at the commencement of the exposure, followed by a steep decline in the amount of pyrethrin I. The duration of the initial lag period is largely, but probably not wholly, a function of the frequency of stirring. In the above cases the dusts were stirred every half-hour, but if the periods between stirring are lengthened the lag period becomes greater, thus if a rich dust is stirred twice a day during exposure the rapid decline in pyrethrin I does not take place until after some ten hours. This is partly explicable on the grounds that the reaction is a surface one. Pyrethrin II appears to be destroyed more slowly, on the whole, than pyrethrin I, particularly towards the end of the exposure. Extracts of the dusts exposed for 16 and 50 hours have still a small residual activity.

Exposure of methyl alcoholic extract of pyrethrum. A preliminary test on the effect of the exposure to sunlight and air of a methyl alcoholic extract of pyrethrum was carried out. The solution was placed in a cylindrical glass vessel to which was attached a condenser, and a stream of air was passed through the apparatus by means of a small electric pump. Thorough aeration of the solution was brought about by passing the air through a sintered glass plate at the bottom of the vessel. The apparatus was exposed to bright sunlight in a warm glasshouse. The radiation figures on the days of exposure were of a constant high level. The temperature throughout the experimental period approximated closely to 25° C.

The solution was prepared for exposure by the extraction of Harpenden grown flowers (1932 crop) with petroleum ether, removal of the solvent, the residue being then extracted with five portions of 20 c.c. of warm methyl alcohol. Each alcoholic extract was cooled, and filtered.

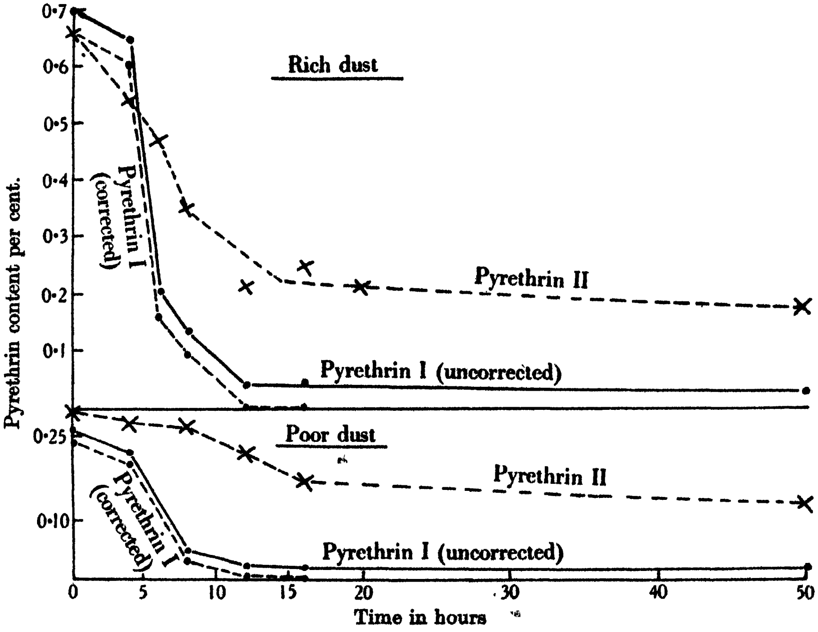

Fig. 3. Decline in pyrethrin values on exposure of rich and poor dusts.

The combined filtrates were adjusted to a volume of 100 c.c. During exposure small amounts of a colourless precipitate were deposited. At intervals this was filtered and washed and 10 c.c. portions of the clear solution were taken, the methyl alcohol was removed *in vacuo*, and the residue extracted with successive portions of low boiling petroleum ether, with gentle warming. The petroleum ether was evaporated in a current of carbon dioxide and the residue taken up with five portions of 2·5 c.c. methyl alcohol, with cooling and filtration of each fraction. To the combined methyl alcoholic extracts, 5 c.c. of *N* methyl alcoholic potash were added, and following saponification, determination of the pyrethrins made by the acid method.

The amounts of pyrethrins I and II present in 10 c.c. of the solution at different stages in the exposure were as follows:

Exposure	Pyrethrin I mg. per 10 c.c.	Pyrethrin II mg. per 10 c.c.
At start 0 hours	90·17	76·38
8 „	53·85	63·04
16 „	26·83	50·09
44 „	4·12	21·69
90 „	0·87	3·39

The logs of the pyrethrin figures are plotted against the times of exposure in Fig. 4.

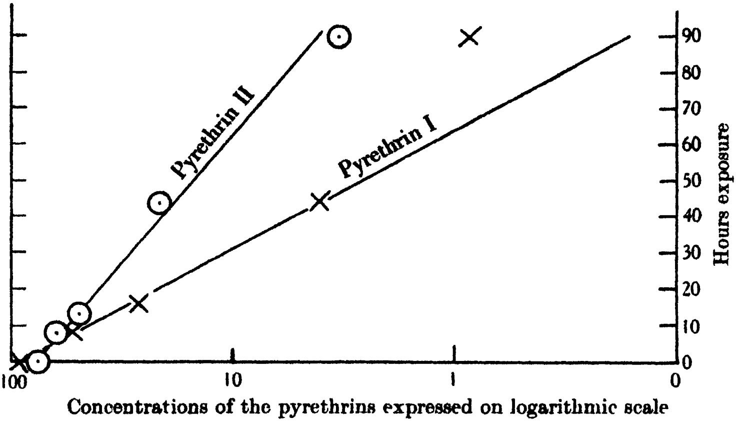

Fig. 4. Decline in pyrethrin content of aerated pyrethrum extract in methyl alcohol solution on exposure to sunlight.

It is seen that four out of the five points in the case of pyrethrin I, and five of the points for pyrethrin II fall very near to straight lines. The lag in the early stages of exposure was not appreciable. The last point for pyrethrin I shows a departure from the line, and we suspect that this discrepancy is probably due to non-pyrethrin material. If the remaining points on the diagram are corrected for this residual value, they still show a linear relationship. The loss of pyrethrin I under these conditions of exposure, as with the pyrethrinised dust, is more rapid than that of pyrethrin II, but we are unaware of the extent to which the reactions influenced each other. It is probable that valuable information on loss of toxicity may be obtained from further carefully controlled experiments on the exposure of the pyrethrins in solution.

Exposure of pyrethrum flowers to sunlight. In Table VIII are set out the data obtained for five samples of pyrethrum in different states of fineness of division, under different conditions of exposure.

Table VIII. *Exposure of pyrethrum flowers in various ways.*

Finely ground, coarsely ground, and whole heads.

Exposure	Harpenden		Dalmatian 1606 Open flowers		Dalmatian 1607 Open flowers		Dalmatian 1608 Half-closed		Dalmatian 1609 All closed	
	Pyrethrin I	Pyrethrin II	Pyrethrin I	Pyrethrin II	Pyrethrin I	Pyrethrin II	Pyrethrin I	Pyrethrin II	Pyrethrin I	Pyrethrin II
FINELY GROUND.										
At start	0·73	0·78	0·19	0·21	0·26	0·31	0·30	0·26	0·43	0·38
90 days:										
Glasshouse open trays	0·16	0·46	0·05	0·20	0·05	0·23	0·09	0·17	0·14	0·23
Glasshouse covered trays	0·67	0·59	0·20	0·24	0·25	0·32	0·28	0·24	0·37	0·36
Glasshouse in tins	0·71	0·68	0·21	0·19	0·26	0·28	0·28	0·23	0·37	0·28
Cellar in tins	0·66	0·65	0·19	0·21	0·25	0·32	0·27	0·23	0·36	0·29
177 days:										
Glasshouse open trays	0·04	0·23	0·02	0·13	0·02	0·20	0·02	0·10	0·04	0·14
Glasshouse covered trays	0·65	0·70	0·19	0·20	0·25	0·30	0·25	0·23	0·34	0·32
Glasshouse in tins	0·65	0·66	0·18	0·25	0·26	0·31	0·28	0·25	0·35	0·36
Cellar in tins	0·67	0·69	0·19	0·23	0·26	0·31	0·26	0·25	0·36	0·35
365 days:										
Glasshouse open trays	0·02	0·11	0·01	0·06	0·01	0·06	0·01	0·05	0·03	0·07
Glasshouse covered trays	0·56	0·63	0·16	0·22	0·25	0·29	0·20	0·19	0·27	0·27
Glasshouse in tins	0·57	0·67	0·20	0·23	0·26	0·28	0·24	0·19	0·33	0·30
Cellar in tins	0·65	0·74	0·20	0·25	0·25	0·32	0·24	0·25	0·35	0·36
COARSELY GROUND.										
At start	0·66	0·63	0·16	0·19	0·24	0·25	0·28	0·24	—	—
90 days:										
Glasshouse open trays	0·20	0·42	0·06	0·16	0·09	0·21	0·08	0·12	—	—
Glasshouse covered trays	0·55	0·57	0·15	0·17	0·22	0·24	0·22	0·19	—	—
Glasshouse in tins	0·63	0·62	0·15	0·16	0·22	0·23	0·21	0·18	—	—
Cellar in tins	0·63	0·62	0·15	0·18	0·22	0·25	0·22	0·18	—	—
177 days:										
Glasshouse open trays	0·05	0·19	0·03	0·14	0·03	0·18	0·03	0·09	—	—
Glasshouse covered trays	0·60	0·60	0·15	0·17	0·22	0·27	0·20	0·18	—	—
Glasshouse in tins	0·61	0·60	0·15	0·20	0·22	0·26	0·22	—	—	—
Cellar in tins	0·59	0·62	0·15	0·19	0·22	0·28	0·22	0·21	—	—
365 days:										
Glasshouse open trays	0·02	0·09	0·02	0·07	0·02	0·08	0·01	0·03	—	—
Glasshouse covered trays	0·52	0·52	0·15	0·17	0·21	0·24	0·16	0·14	—	—
Glasshouse in tins	0·51	0·57	0·15	0·16	0·21	0·24	0·18	0·17	—	—
Cellar in tins	0·55	0·55	0·17	0·19	0·24	0·25	0·19	0·16	—	—
WHOLE HEADS.										
At start	0·73	0·78	0·19	0·21	0·26	0·31	0·30	0·26	0·43	0·38
90 days:										
Glasshouse open trays	0·59	0·79	0·19	0·22	0·23	0·26	0·18	0·20	0·38	0·37
Glasshouse covered trays	0·79	0·61	0·21	0·21	0·25	0·23	0·23	0·20	0·34	0·35
Incubator at 28° C.	0·72	0·66	—	—	—	—	—	—	—	—
365 days:										
Glasshouse open trays	0·44	0·60	0·11	0·15	0·18	0·23	0·18	0·18	0·31	0·27
Glasshouse covered trays	0·67	0·53	0·20	0·23	0·24	0·26	0·25	0·21	0·36	0·32
Glasshouse in tins	0·61	0·68	0·17	0·19	0·25	0·28	0·25	0·25	0·37	0·32
Cellar in tins	0·62	0·58	0·19	0·19	0·30	0·30	0·24	0·22	0·45	0·32
Incubator at 28° C.	0·64	0·65	—	—	—	—	—	—	—	—

Each of the samples of pyrethrum was divided into three parts. One part was ground to pass a sieve, the mean diameter of the holes of which was 0·584 mm., and the second ground to pass a sieve, the mean diameter of the holes of which was 1·72 mm. We have referred to these samples respectively as finely and coarsely ground flowers. The third was left as whole heads. Each of these subsamples was again divided into four parts, one of which was exposed in a thin layer to direct sunlight in the glasshouse, a second was kept in trays in the glasshouse but protected by a cover from sunlight, the third in closed tins in the glasshouse, and the fourth in tins in a cool cellar. One sample of the Harpenden flowers (whole heads) was placed in a closed tin in an incubator kept at 28° C. The samples were stirred each week. The ground samples were tested at the end of 90, 177 and 365 days, and the whole heads at the end of 90 and 365 days. In the results given, no deduction has been made in the pyrethrin I estimation to allow for any residual non-pyrethrin value. The data show that with the fine and coarsely ground dusts loss of pyrethrin I is rapid in sunlight, there being little to distinguish the coarse from the finely ground sample. There is a slow loss in the case of the ground samples exposed in the covered trays and in the tins in the glasshouse, with the exception of the poor samples 1606 and 1607, where it is negligible. In the case of the whole heads, sampling is difficult, and errors due to this cause may be large, but the conclusion can be drawn that they lose their pyrethrin I at a very much slower rate than the ground flowers. Nevertheless, in the presence of sunlight the loss is definite both after 90 and 365 days. There would appear to have been a slight loss after 365 days in the whole flowers kept covered or in tins in the glasshouse. These results tend to confirm the data of Gnadinger and Corl(5) who have pointed out that losses take place on storage in sealed containers.

Exposure of pyrethrinised dusts and pyrethrum powder in sealed flasks. An attempt to determine the extent to which oxygen is requisite to loss was made by exposing a pyrethrinised dust and ground pyrethrum powder in rubber-stoppered flasks in an atmosphere of nitrogen and air. 6 gm. of the dusts and powders were weighed in the dark into each of the flasks (volume 100 c.c.), which were then evacuated. Nitrogen, which had passed through several vessels containing alkaline pyrogallic acid, was slowly run in. The flasks were again evacuated and nitrogen again passed in, after which inlet and outlet tubes of each flask were sealed. In the case of exposure to an atmosphere of air, 6 gm. were weighed into each of a series of 100 c.c. flasks and these were closed with solid rubber stoppers. Each of the two sets of flasks was divided into three subsets, which were exposed in the following ways: (1) in a cool cellar in the dark, (2) to the light in a glasshouse, (3) in the dark at 28° C. in an incubator. The flasks were shaken at least every second day. Analyses were carried out at the end of 8, 36, 72 and 196 days. No correction by deduction was applied to the estimation of pyrethrin I. The results are given in Table IX.

Table IX. *Exposure of pyrethrinised dust and pyrethrum powder in sealed flasks.*

	Nitrogen		Air	
Exposure	Pyrethrin I %	Pyrethrin II %	Pyrethrin I %	Pyrethrin II %
Pyrethrinised dust (pyrethrin I 0·46 %, pyrethrin II 0·45 %):				
Cellar (18° C.) 8 days	0·46	0·45	0·45	0·45
Glasshouse 8 days	0·40	0·41	0·22	0·38
Incubator (28° C.) 8 days	0·49	0·47	0·42	0·45
Cellar (18° C.) 36 days	0·44	0·40	0·43	0·38
Glasshouse 36 days	0·22	0·20	0·05	0·13
Incubator (28° C.) 36 days	0·42	0·41	0·43	0·39
Cellar (18° C.) 72 days	0·46	0·44	0·43	0·42
Glasshouse 72 days	0·21	0·22	0·05	0·16
Incubator (28° C.) 72 days	0·42	0·38	0·41	0·38
Cellar (18° C.) 196 days	0·42	0·44	0·42	0·46
Glasshouse 196 days	0·06*	0·10*	0·04	0·08
Incubator (28° C.) 196 days	0·37	0·35	0·24	0·25
Pyrethrum powder (pyrethrin I 0·45 %, pyrethrin II 0·49 %):				
Cellar (18° C.) 8 days	0·43	0·53	—	—
Glasshouse 8 days	0·39	0·49	0·34	0·48
Incubator (28° C.) 8 days	0·43	0·50	0·44	0·48
Cellar (18° C.) 36 days	0·42	0·43	0·40	0·43
Glasshouse 36 days	0·30	0·33	0·11	0·33
Incubator (28° C.) 36 days	0·39	0·44	0·39	0·41
Cellar (18° C.) 72 days	0·41	0·49	0·43	0·46
Glasshouse 72 days	0·30	0·37	0·07	0·33
Incubator (28° C.) 72 days	0·37	0·35	0·37	0·39
Cellar (18° C.) 196 days	0·42	0·47	0·41	0·49
Glasshouse 196 days	0·23	0·27	0·04	0·19
Incubator (28° C.) 196 days	0·37	0·41	0·37	0·40

* Air apparently had leaked in.

The figures for the estimation of pyrethrin I show that when pyrethrum dusts and powders are exposed in air to sunlight there is the usual rapid loss, but that the loss is somewhat slower in the case of powdered flowers than the artificially prepared dusts. The loss is definitely slower in an atmosphere of nitrogen than in air. We suspect that after 72 days there may have been a leakage of air into the flasks containing nitrogen and exposed in the glasshouse, as the values which had remained constant from 36 to 72 days declined more rapidly. We cannot be sure that a little oxygen was not occluded with the dusts nor do we know the part played by adsorbed moisture, but the experiment tends to show that free oxygen may not be requisite for slow losses. Comparisons of the results obtained from exposure in tins in the incubator and in the cool cellar indicate that there is a greater loss at the higher temperature. Gnadinger and Corl (5) have shown that activity of pyrethrum declines more slowly at low temperatures than at high temperatures. Our results confirm this finding and the determination of the temperature coefficient might be of interest.

Other experiments were carried out in glass bulbs of about 70 c.c. capacity, having inlet tubes running about half-way to the bottom, and outlet tubes sealed also into the top. 6 gm. of a pyrethrinised dust were weighed into each tube in the dark, and nitrogen was passed in after being freed from oxygen by running a fine stream of bubbles through a series of sintered glass gas-wash bottles containing strong alkaline sodium hydrosulphite solution. The tubes were then evacuated by a Hyvac pump and nitrogen again passed in. After repeating this process the tubes were sealed, and exposed for a period of 122 days. The tubes were shaken every two days. Table X gives the results:

Table X. *Exposure of pyrethrinised dusts in special tubes.*

Description	Pyrethrin I %	Pyrethrin II %
Composition of dust at start: (1)	0·65	0·48
(2)	0·65	0·51
Dust in air exposed to sunlight after 122 days	0·17	0·22
Dust in nitrogen exposed to sunlight after 122 days	0·47	0·37
Dust in air in incubator in dark at 48° C. 122 days	0·40	0·36
Dust in nitrogen in incubator in dark at 48° C. 122 days	0·58	0·50
Dust in nitrogen in cool cellar in dark 122 days	0·64	0·56

Although it is impossible to be certain that no traces of oxygen were occluded in the tubes filled with nitrogen, the amount present must have been very small, and it is fairly evident from the above that losses of pyrethrin can take place in the presence of an inert gas, although at a much slower rate than in air, and that loss in nitrogen takes place in the incubator at 48° C. but again at a slower rate than in air. The dust exposed both to nitrogen and air in the incubator at the relatively high temperature of 48° C. suffers appreciable loss of pyrethrin I, although this is not so great in either case as in sunlight. The decline in pyrethrin I in nitrogen is greater at 48° than in the cool cellar (temperature approximately 18° C.) where the loss was found to be infinitesimal.

Chemical evaluation of exposed pyrethrinised dusts containing antioxidants. The antioxidants used in this trial were tannic acid and hydroquinone. The dusts were prepared by extracting Harpenden grown flowers (1932 crop) with low-boiling petroleum ether, the concentrated extract was mixed with finely divided talc, and the petroleum ether removed *in vacuo* after thorough mixing. The dust was divided into three portions of 50 gm. each: to one was added 1·25 gm. of hydroquinone, another 1·25 gm. of tannic acid, while the third portion was kept as a control. The hydroquinone and the tannic acid were incorporated into the dusts in solution in the minimum amount of absolute alcohol, which was finally removed *in vacuo*. 5 gm. portions of the control and treated dusts were then exposed in shallow trays to a 1000-watt lamp, with stirring at regular intervals of half an hour. Different exposure periods up to 40 hours were used, and the pyrethrin I content of the dusts at the end of each exposure was determined. We have made no attempt to correct the figures for pyrethrin I. It is obvious from the data that these antioxidants have a stabilising effect upon activity and it is possible that this may be sufficiently marked to extend the use of pyrethrinised dusts. It is, however, questionable whether, owing to difficulties of thorough incorporation, the stabilising effect would be so noticeable with powdered flowers. The data are given in Table XI and expressed in Fig. 5.

Table XI. *Exposure of pyrethrinised dusts with and without antioxidants.*

Exposure hours	Pyrethrin I, % of dust		
	Control	Tannic acid	Hydroquinone
At start	0·59	0·45	0·57
5	0·46	0·40	0·52
10	0·28	0·36	0·49
15	0·08	0·33	0·44
20	0·04	0·26	0·34
30	0·03	0·15	0·24
40	0·04	0·10	0·17
Cellar in tins	0·61	0·47	0·58

Loss of colour of pyrethrinised dusts. The question has been raised from time to time whether the colour of ground pyrethrum flowers is in any way correlated with activity. We have noted, during our work on the exposure of dusts, that the colour began to fade in samples untreated by antioxidants many hours before a similar loss occurred in treated samples, and also that the fading of the colour was about complete in the same time as the pyrethrin I value required to fall to an almost negligible level. For example, after 40 hours' exposure there was a distinct loss of colour in the tannic acid treated dust and partial loss in the case of the hydroquinone treated dust, while the untreated dust was colourless.

The rapid loss in the colour of the untreated dust was followed by determining the changes in the absorption bands of a clear alcoholic extract. The extract of the non-exposed dust showed a strong absorption band at 6750–6640 Å., very faint bands at 6100 and 5350 Å., while the violet end of the spectrum was extinguished from 5010 Å. The band in the orange region could not be seen after 12 hours, while, as exposure proceeded, the band in the violet region decreased gradually, disappearing entirely after 16 hours, when the dust appeared colourless. The points marked × in Fig. 5 show the retraction of the broad band in the violet

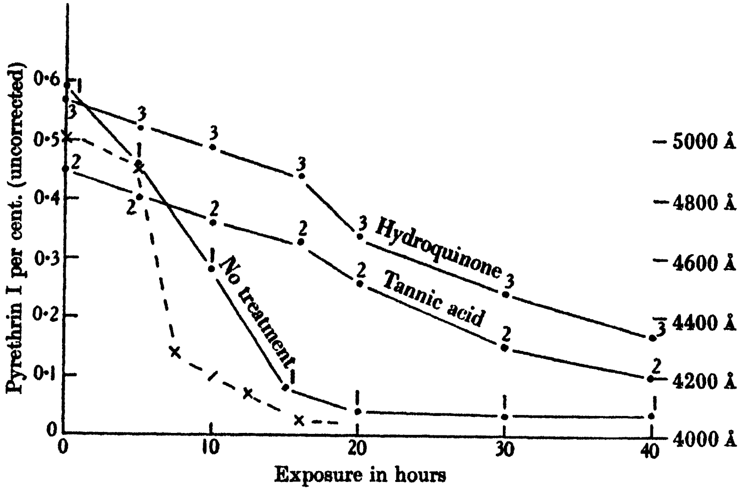

Fig. 5. Loss of pyrethrin I in pyrethrinised dust with and without antioxidants on exposure to 1000-watt lamp.

●^{1} ●^{1} Untreated dust.
●^{2} ●^{2} Tannic acid treatment.
●^{3} ●^{3} Hydroquinone treatment.
× × Retraction of absorption band.

on exposure of the untreated dust. There was no attempt to measure by means of the spectrophotometer the decreasing intensity of the band, but the points indicate that during exposure the violet band had retracted to much smaller dimensions by the time that the pyrethrin I value had fallen almost to zero. It is doubtful, however, whether there is any rigid connection between colour and activity, but there is a possibility that certain plant pigments, owing to their structure, *e.g.* the anthoxanthins, might have a stabilising effect against oxidation. It is also probable that the factors making for loss of colour are closely related to those making for loss of activity in pyrethrum when the latter is exposed to light and air.

DISCUSSION.

An attempt has been made in the foregoing pages to submit an analytical criticism of some of the results obtained in a preliminary investigation (*loc. cit.*) of the causes of the loss of activity of pyrethrum, when exposed to light and air. One of the limiting factors in the use of pyrethrum as an insecticide has been the fugitive nature of its activity. In addition, we believe that the difficulties and discrepancies of investigation have been increased by the labile nature of the active principles.

The loss of activity of pyrethrinised dusts on exposure may be followed with a good, but not absolute degree of accuracy by the determination of pyrethrin I. There is a small residual value left after exposure, with which the biologically determined insecticidal activity is not in strict correlation[1], and by deducting this residual value the concordance between the estimation of pyrethrin I and toxicity is increased. Although in the case of normal rich flowers and dusts the correction may be so small as hardly to affect the results and scarcely outside the degree of discrepancy of two different investigators, it may become of greater importance in the case of poor samples.

We have exposed both flowers and artificially prepared dusts in air to sunlight, and the dusts to the illumination of a 1000-watt lamp for varying periods, and find that, after an initial lag period, the rate of loss of activity is rapid and then decreases. It was found that in a methyl alcoholic extract of the flowers, exposed to a rapid stream of air in the presence of strong sunlight, the lag period was scarcely evident. Considering the loss in solution of pyrethrins I and II separately, the data over a large part of the exposure period corresponded in each case fairly closely with an unimolecular reaction, the rate of loss of pyrethrin II being slower than that of pyrethrin I. This conclusion, however, will require confirmation. When flowers are exposed to sunlight and air we were able to confirm the fact that powdered heads lose their activity more rapidly than whole heads. It was found that, although light accelerates loss by some process of activation, losses could take place in the dark and that there was apparently a temperature coefficient. Gnadinger and Corl (5) have found that, at a low temperature, loss of activity is practically negligible. In a series of experiments in which powders and artificially prepared dusts were sealed in nitrogen it was found by us that loss of pyrethrin I took place, although at a materially slower rate than in air. Furthermore, in the presence of nitrogen, the loss of pyrethrins seems to take place more rapidly at higher than at lower temperatures and also to be accelerated by light. It is recognised that to free our dusts and powders from the last traces of oxygen may not be easy, but it appears that pyrethrum may degenerate by processes other than oxidation by *free* oxygen. The presence of adsorbed moisture in this connection is probably of importance.

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[1] The nature and extent of this apparent discrepancy is now being examined.

Both by biological trials and analytical tests we have confirmed the partial stabilising effect of the addition of antioxidants, but the suggestions that antioxidants might lead to an enhanced toxicity of the pyrethrins in sprayed pyrethrum extracts was not confirmed. The fading of the colour of pyrethrinised dusts in light and air and its partial stabilisation by the incorporation of antioxidants have been noticed. The gradual contraction of the broad band in the violet end of the spectrum was observed to run roughly parallel with the loss of pyrethrin I. Although no direct connection can be traced between the degree of colour and activity, and between loss of colour and loss of activity, it would appear as if the same causes were leading to these parallel effects. Whether any of the naturally occurring colour pigments, either through an antioxidation effect or through preferential absorption of light, lead to a stabilising action is a matter of some interest. So far, with the few synthetic dyes experimented with, we have not been able to secure results of a definite nature.

SUMMARY.

1. The loss of activity of pyrethrum flowers and preparations has been studied.

2. The degree of concordance between the content of pyrethrin I, as determined by the acid method, and the insecticidal value of pyrethrinised dusts, before and after exposure to air and artificial illumination, has been statistically examined. The pyrethrin I values, corrected for a small residual amount of extraneous matter, indicate fairly closely the degree of activity of the samples. The loss of pyrethrins on exposure has been traced out quantitatively.

3. A comparison was made between two samples of pyrethrum flowers, one rich and the other poor in pyrethrins, in order to determine the degree of concordance between the pyrethrin I content and their toxicity. The pyrethrin I value as determined by the acid method, subject to a small correction, gave a good indication of the relative activities of the samples.

4. Pyrethrum flowers, both finely and coarsely ground and as whole heads, have been exposed under various conditions for different periods up to one year. There was a relatively rapid loss of pyrethrin I in cases

where the ground flowers were exposed to sunlight and air, but when stored in covered trays or tins the loss of pyrethrin I was much slower. The pyrethrins undergo change at a slower rate in flowers stored as whole heads than in the ground state.

5. Pyrethrinised dusts and ground flower heads lose their pyrethrin content when exposed to sunlight in an atmosphere of air or of nitrogen. The loss in nitrogen is less rapid than in air and appears to be due to a reaction other than oxidation by free oxygen. The effect of temperature upon the rate of loss of the pyrethrins is shown.

6. The rate of loss of the pyrethrins in a methyl alcoholic extract of flowers, when exposed to sunlight and air, was studied.

7. The stabilising effect of tannic acid and hydroquinone when added to a talc pyrethrum dust was confirmed. It was shown that such mixtures lose their pyrethrins at a slower rate when exposed in thin layers to air and artificial illumination. Biological trials showed that the addition of these antioxidants did not augment the initial insecticidal activity of the pyrethrins.

We have found during the course of this work that Dr C. I. Bliss's system of probits has afforded us a powerful and simple device for the statistical analysis of our results. We wish to express to him our thanks for advance copies of his tables and for his advice. We wish also to acknowledge with our thanks the help and assistance afforded to us by Mr P. C. Bowes, Mr A. Ogglesby and Miss I. P. Randall. We are also indebted to Messrs Stafford Allen and Co., Ltd., for kindly supplying us with Dalmatian samples of pyrethrum.

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THE DETERMINATION OF WINTER-HARDINESS IN OATS.

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Introduction.

When assessing the value of any variety of a commercial plant one is concerned with a number of different features of the plant's behaviour, among others winter-hardiness. The behaviour with regard to most of these features is tested by methods which have been carefully planned and whose reliability has been proved, but the determination of winter-hardiness is still a matter of observing the reaction of the plants to the conditions prevailing at that season of the year. However, in England, particularly in the southern counties, the winters are comparatively mild and it is only occasionally that the climate provides a really good test of the plant's resistance. On the other hand it is necessary to have some knowledge of the winter-hardiness of a variety, since otherwise disastrous results may follow on a really hard winter. A method of determining the resistance of new varieties in the laboratory would provide the solution to this problem.

Since very cold winters are those which result in most damage to the crop it might be supposed that the winter-hardiness of a variety is mainly determined by the resistance to low temperatures as was demonstrated for wheat by Åkerman and Lindberg (1927). It is the object of this paper to present an account of comparisons of cold resistance, as determined in the laboratory, and winter-hardiness as determined in the field, of certain English oat varieties.

With the physiological factors affecting freezing resistance we are not concerned—an account of this aspect of the problem is given by Åkerman and Lindberg (1927) for wheat varieties. The present work is very largely an extension of Prof. Åkerman's work but in a slightly different direction.

No winter oats are grown in Sweden, so English oats were chosen for the experiments. The material was obtained from the National Institute of Agricultural Botany, Cambridge, and consists of four well-known varieties, Abundance, Bountiful, Grey Winter, and Marvellous, and of a number of new forms now under test and having no names. These will be referred to under numbers. The majority of these types, viz. 109/1/5, 109/3/8, the *ex* 109/1 series, 125/3, 136/17, 105/8, and 116/1, have been raised by Dr H. Hunter of Cambridge, to whom we are indebted for the information as to their origin and behaviour in England. They all came from the cross Grey Winter × Argentine, and the *ex* 109/1 series resulted from what may have been a natural cross of 109/1, a white form, with a grey type, possibly a back-cross to Grey Winter.

FIELD OBSERVATIONS.

In Table I will be found the survival percentages of some well-known varieties after spring and autumn sowings in different years in England. Excluding for the moment the winter of 1928–9, which was one of unusual severity, it will be seen that there is little to choose between the different varieties and that the spring and winter sowings give, on the whole, very similar figures—figures which most certainly show no

Table I. *Survival percentages at harvest of a number of different English oat varieties after autumn* (A.) *and spring* (S.) *sowings during a number of years.*

	1926–7		1927–8		1928–9		1929–30		1930–1	
	A.	S.	A.	S.	A.	S.	A.	S.	A.	S.
Grey Winter	86	83	85	74	87	78	89	62	86	84
Avoine d'Hiver	89	82	86	78	54	89	81	57	72	84
Abundance	86	76	90	69	0	81	77	66	84	89
Bountiful	96	87	79	54	0	80	86	77	89	84
Marvellous	85	—	80	59	0	90	80	83	84	87
Argentine	90	82	86	65	0	84	87	66	73	86

Survival percentages at harvest of the parents and some offspring of the cross Grey Winter × Argentine after autumn sowing during a number of years.

	1928–9	1931–2	1932–3
Grey Winter	87	90	88
Argentine	0	—	—
105/8	78	—	—
109/1	69	—	92
109/3	64	95	—
136/17	Poor	93	—
ex 109/1 C. 1	—	—	85
ex 109/1 C. 7	—	—	88
ex 109/1 C. 10	—	—	91

125/3 showed fair survival in the year 1928–9

advantage for the spring sowing. This is a very clear demonstration of the mildness of the English winter in Cambridge, where these results were obtained.

Now turning to the 1928–9 results, there is a very different state of affairs. That winter was one of unusual severity, and these results clearly show that the varieties reacted very differently to it. Abundance, Argentine, Bountiful and Marvellous were entirely killed, but Grey Winter and the closely related French form, Avoine d'Hiver, show quite good survival at the subsequent harvest. This marks a great distinction between the winter-hardiness of the two groups of varieties.

Turning to the new varieties, for which the results are necessarily not so complete, it will be seen that the situation is very much the same. In the normal mild winters, *e.g.* 1931–2 and 1932–3, all show over 80 per cent. surviving till harvest after autumn sowing. Again, however, the hard winter of 1928–9 brings out marked differences. 105/8, 109/1, and 109/3 show survival percentages which are quite good, but 125/3 is only fair and 136/17 is definitely not winter-hardy at all.

The *ex* 109/1 series were not available for observation during that hard winter, and as to the remaining varieties we have no information.

The results of the Swedish field tests are given in Table II. These consist of only one year's observations, but, although this winter was mild for Skåne, the climate was severe enough to show up marked differences in the resistance of the different varieties.

The effects of wintering were estimated in two ways at Svalöf. First, in March the general appearance of the plots (four replicates of each variety) was taken into account and a number allocated to each. 1 denotes complete extinction, and 5 shows lack of injury by the winter. The marks of the four replicates were averaged and the mean figure is given in Table II. Secondly, the percentage of plants surviving on April 30 was determined. There were two different sowings of the oats in the autumn and the percentage survival differs for these, so they are given separately in Table II.

The results in general show a marked similarity to the English 1928–9 results. Abundance, Bountiful, Marvellous and 136/17 are killed by the winter, whereas Grey Winter, 105/8, 109/3, and 109/1 survive reasonably well. It will be seen that the best survival and most healthy-looking plants are given by the *ex* 109/1 series, particularly culture 1. As noted above there are unfortunately no comparable English results. Of the other numbered varieties s. 82 gave quite good results while s. 81 and 1/2/3/54 are fair.

Table II. *The degree of frost injury (first column) and survival percentages (second and third columns) of various oat varieties after a mild Swedish winter. (Data from Svalöf.)*

	Degree of frost injury—March	[illegible]	
		First sowing	Second sowing
Grey Winter	2·0	12·7	7·7
	2·0	18·7	8·0
Marvellous	1·0	0·0	0·3
	1·0	0·0	0·0
Bountiful	1·0	0·0	0·3
	1·0	1·0	0·0
Abundance	1·0	0·0	0·0
	1·0	1·0	0·0
109/3/8	2·3	36·7	29·7
	2·8	62·0	14·7
109/1/5	2·6	46·7	19·0
ex 109/1 C. 1	2·9	63·0	40·3
ex 109/1 C. 5	2·9	55·0	41·0
ex 109/1 C. 6	2·9	46·7	41·3
ex 109/1 C. 7	2·9	47·7	30·3
125/3	1·5	11·3	12·7
105/8	1·8	23·9	8·0
116/1	1·4	9·0	4·7
136/17*a*	1·0	0·7	0·3
	1·0	1·0	0·0
136/17*b*	1·0	0·3	0·3
s. 81	1·9	19·7	10·7
s. 82	2·0	41·0	27·3
1/2/3/54	2·0	28·0	10·0

It may be noted that some of the varieties were grown in duplicate besides the fourfold replication of all the plots. The duplicate results are in very good agreement except those for the variety 109/3/8. This variety will be referred to again in this connection.

In general it may be said that the Swedish trial gives very similar results to the English ones as to the winter resistance of the different varieties tested in both countries.

Freezing experiments.

The freezing resistance of the varieties was determined in the laboratory by the following method.

The seeds were sown in wooden boxes in the autumn and the plants were left outside in cold frames until needed. At various times during the winter determinations were made. For this purpose a number of plants (usually ninety) of each variety were transplanted into metal boxes filled with sand. They were then hardened off by standing in temperatures of 2° C. and −2° C. for two days and were finally placed in the freezing chambers at the desired temperatures for twenty-four hours. Three were used in each experiment and thirty plants at each temperature. Afterwards they were brought back to the cold house for thawing and left at room temperature for a week or more when the estimation of freezing injury was made. This was done by grading the individual plants into five classes, viz. 1–5, class 1 being those completely dead and class 5 those completely uninjured. The figures for the thirty plants of each kind were then averaged and the mean figure taken as a measure of the resistance of that variety to freezing injury. Four determinations were made at different temperatures and times during the winter of 1932–3 and five during the winter of 1933–4. The results are given in Table III. The degree of injury was found to vary with the time of determination as well as with the temperature used.

Table III. *Primary figures obtained by the different varieties in the freezing trials. The first two trials in* 1933–4 *were made approximately six weeks before the last three.*

	1932–3				1933–4				
	-8° C.	−9° C.	−12° C.	−13° C.	10° C.	−12° C.	-9° C.	−11° C.	−13° C.
Grey Winter	2·3	1·9	2·0	1·6	1·8	1·6	3·7	3·9	2·3
	3·3	2·4	1·5	1·8	1·5	1·5	3·2	2·6	1·9
Marvellous	1·7	1·6	1·0	1·0	1·3	1·1	2·9	3·2	2·2
	1·8	1·5	1·0	1·0	1·1	1·0	2·9	2·3	1·5
Bountiful	1·4	1·7	1·1	1·0	1·2	1·1	3·8	3·5	2·0
	1·3	2·3	1·0	1·1	1·0	1·0	2·6	1·5	1·0
Abundance	1·4	1·4	1·0	1·0	1·1	1·0	3·5	2·6	1·3
	1·3	2·1	1·2	1·0	1·1	1·0	—	—	—
109/3/8	2·4	2·1	2·0	1·4	1·5	1·4	3·5	3·9	2·6
	3·5	2·6	2·3	1·4	1·5	1·5	4·6	4·0	3·0
109/1/5	3·4	2·2	2·1	1·6	1·7	1·5	3·5	2·8	2·3
ex 109/1 C. 1	3·3	2·1	2·4	1·6	1·8	2·0	4·5	4·1	2·6
ex 109/1 C. 5	3·6	2·5	2·4	1·5	1·9	2·0	3·8	3·2	2·7
ex 109/1 C. 6	3·0	2·4	2·3	1·8	2·1	2·3	3·0	3·1	3·2
ex 109/1 C. 7	3·4	2·2	2·2	1·4	1·9	1·9	3·2	3·3	2·9
125/3	2·5	1·8	1·9	1·2	1·5	1·4	3·4	3·4	2·3
105/8	3·2	2·1	1·6	1·3	1·2	1·3	3·6	3·5	2·7
116/1	2·5	2·2	1·3	1·1	1·2	1·4	3·6	2·1	2·0
136/17	1·3	1·9	1·0	1·0	1·1	1·0	3·0	2·1	2·1
	1·5	1·8	1·0	1·0	1·3	1·1	3·1	2·1	1·4
	2·2	1·6	1·2	1·1	1·0	1·5	2·2	3·5	1·2
s. 81	2·7	2·3	1·5	1·1	1·3	1·5	3·8	3·4	1·8
s. 82	3·4	2·2	1·4	1·2	1·3	1·7	3·9	3·6	1·9
1/2/3/54	2·7	1·9	1·3	1·1	1·4	1·2	3·5	2·2	2·0
Mean	2·4	2·0	1·6	1·3	1·4	1·4	3·4	3·0	2·1

The results of the different experiments were reduced to a more comparable state by taking the average injury figure for all the varieties in any experiment, putting this as equal to ten and recalculating the individual varietal figures on this basis. Table IV gives these figures for the varieties in all the experiments (columns 2–10) and also the mean figure for each variety's behaviour in all the experiments combined (column 11). The bottom row of the table gives the actual figure for all the varieties in each experiment. It will be seen from this row that the freezing resistance of the varieties varies considerably from time to time, but the data is not extensive enough for any discussion. It does, however, appear that the resistance increases as the time after sowing increases, possibly as a result of the hardening off process which the plants experience in the cold frames. It will also be seen that the individual varieties show some fluctuation in the different experiments, but this is on the whole not marked. The mean figure for the whole series of experiments is the really important one, as it represents the average behaviour of the variety under a number of different conditions at different times, *i.e.* is more of a measure of the general freezing resistance of the plants throughout the winter. This is the figure for each variety which will be used in making comparisons.

Table IV. *Balanced results of the freezing experiments (for explanation see in the text).*

	1932–3				1933–4					Mean
Grey Winter	9·6	9·5	12·5	12·3	12·9	11·4	10·9	13·0	10·9	11·4
	13·7	12·0	9·4	13·8	10·7	10·7	9·4	8·7	9·0	10·8
Marvellous	7·1	8·0	6·3	7·7	9·3	7·7	8·5	10·7	10·5	8·4
	7·5	7·5	6·3	7·7	7·7	7·1	8·5	7·7	7·1	7·5
Bountiful	5·8	8·5	6·9	7·7	8·7	7·7	11·2	11·7	9·5	8·6
	5·4	11·5	6·3	8·5	7·1	7·1	7·6	5·0	4·8	7·0
Abundance	5·8	7·0	6·3	7·7	7·7	7·1	10·3	8·7	6·2	7·4
	5·4	10·5	7·5	7·7	7·7	7·1		Dead		7·6
109/3/8	10·0	10·5	12·5	10·8	10·7	10·1	10·3	13·0	12·4	11·1
	14·6	13·0	14·4	10·8	10·7	10·7	13·5	13·3	14·3	12·8
109/1/5	14·2	11·0	13·1	12·3	12·1	10·7	10·3	9·3	10·9	11·5
ex 109/1 C. 1	13·7	10·5	15·0	12·3	12·9	14·3	13·2	13·7	12·4	13·1
ex 109/1 C. 5	15·0	12·5	15·0	11·5	13·4	14·3	11·2	10·7	12·9	13·0
ex 109/1 C. 6	12·5	12·0	14·4	13·8	15·9	16·4	8·8	10·3	15·2	13·1
ex 109/1 C. 7	14·2	11·0	13·8	10·8	13·6	13·6	9·4	11·0	13·8	12·3
125/3	10·4	9·0	11·9	9·2	10·7	10·0	10·0	11·3	10·9	10·4
105/8	13·3	10·5	10·0	10·0	8·7	9·3	10·6	11·7	12·9	10·8
116/1	10·4	11·0	8·1	8·5	8·7	10·0	10·6	7·0	9·5	9·3
136/17	5·4	9·5	6·3	7·7	7·7	7·1	8·8	7·0	10·0	7·7
	6·2	9·0	6·3	7·7	9·3	7·7	9·1	7·0	6·7	7·7
	9·2	8·0	7·5	8·5	7·1	10·7	6·5	11·7	5·8	8·3
s. 81	11·2	11·5	9·4	8·5	9·3	10·7	11·2	11·3	8·6	10·2
s. 82	14·1	11·0	8·8	9·2	9·3	12·1	11·5	12·0	9·0	10·8
1/2/3/54	11·2	9·5	8·1	8·5	10·0	8·7	10·3	7·3	9·5	9·2
Mean of experiment	2·4	2·0	1·6	1·3	1·4	1·4	3·4	3·0	2·1	—

A number of the varieties were frozen in duplicate and give an estimate of the accuracy of the determinations. The agreement of the duplicate figures for the varieties in the whole set of experiments is satisfactory in that it is as close as the agreement of the outdoor observations. Again, however, it will be noted that the duplications of the variety 109/3/8 do not show very good agreement, and the deviations go the same way as in the outdoor trials. Since the duplications were made up before the work was commenced it is possible that an error was made in the key list of the varieties.

COMPARISON OF THE FIELD AND LABORATORY RESULTS.

In Table V will be found a résumé of both field and laboratory observations. The most striking feature of this table is the close parallelism of the freezing resistance as determined in the laboratory and winter-hardiness as determined outside under Swedish field conditions. All the standard English varieties tested except Grey Winter show complete death outside and get very low figures in the freezing experiments. Grey Winter, on the other hand, is fair outside and gets a figure above the average inside. Of the new sorts the *ex* 109/1 series is outstanding. They obtained the highest figures inside and show 40 per cent. survival outside after a Swedish winter. This is a remarkably good performance. The other 109 oats are very good but are overshadowed in both sets of observations by the previous series. 125/3, 105/8 and 116/1 are also fair, the last not being so good as the other two either in the freezing experiments or outside, 136/17 are definitely poor in both sets of trials, in fact they are as bad as the majority of the named varieties. Other good features of this variety should, however, make it an extremely

Table V.

	Freezing figure	Percentage survival	
		Sweden (1933–4)	England (1928–9)
Grey Winter	11·4	12·7	87
	10·8	18·7	—
Marvellous	8·4	0·0	0·0
	7·5	0·0	—
Bountiful	8·6	0·0	0·0
	7·0	1·0	—
Abundance	7·4	0·0	0·0
	7·6	1·0	—
109/3/8	11·1	36·7	69·0
	12·8	62·0	—
109/1/5	11·5	46·7	64·0
ex 109/1 C. 1	13·1	63·0	—
ex 109/1 C. 5	13·0	55·0	—
ex 109/1 C. 6	13·1	46·7	—
ex 109/1 C. 7	12·3	47·7	—
125/3	10·4	11·3	Fair
105/8	10·8	23·9	78·0
116/1	9·3	9·0	—
136/17	7·7	0·7	Poor
	7·7	1·0	—
	8·3	0·3	—
s. 81	10·2	19·0	—
s. 82	10·8	41·0	—
1/2/3/54	9·2	28·0	—

valuable spring form. As regards the remaining numbered varieties, s. 82 is quite good both in the laboratory and outside, while s. 81 and 1/2/3/54 are only fair.

The data on the winter survival in England are more fragmentary. As pointed out above the normal English winter is useless for testing the winter-hardiness, but considering the 1928–9 results, they are in good agreement with both the Swedish outdoor results and the freezing experiments. Grey Winter shows a fair survival percentage, while Abundance, Bountiful and Marvellous were completely killed as in Sweden. Of the numbered varieties the *ex* 109/1 series' behaviour is unknown, but 109/1 and 109/3 show good survival while 125/3 is only fair and 136/17 is poor.

With regard to the initial problem of whether the freezing experiments provide a real test of winter-hardiness the answer is most definitely in the affirmative. They parallel in a most remarkable way the results from the Skånish outdoor trials and are in good agreement with the English results as far as they go. The English outdoor results might be expected to differ more from the laboratory determinations than the Swedish as the English winter is much wetter, so differing more from the conditions of the indoor experiments, but it must be admitted that the agreement of the English winter-hardiness results and the freezing resistance results is close enough for the latter to be taken as a good approximate measure of the former.

The value of such a simple and convenient laboratory method of testing winter-hardiness is very great. For example, the *ex* 109/1 series have never been tested under a severe English winter, but the freezing trials indicate that they would stand any winter in England and still produce a good crop. On the other hand, 136/17 will survive the normal winter and on account of its other good features might be extensively grown, but, from the freezing data, if a severe winter came along the whole crop would be lost. Hence it will, in all probability, be better as a spring oat. To sum up, the majority of the varieties might be used as winter oats in England in most years, but there is always the risk of loss in a hard winter. The results of such freezing experiments as are described above provide an indication as to how great the risk of serious damage to the crop is. As such they are valuable.

It must be noted that such freezing trials are of a strictly comparative nature. Some standard variety must always be used in order to compare the behaviour of the new varieties undergoing testing.

In conclusion it is interesting to note that there is segregation for the character of winter-hardiness in the offspring of the cross Grey Winter × Argentine. As is usual with physiological characters of this nature the segregation is not simple, since all grades of winter-hardiness are encountered in the extracted types. In the case of the 109/1/5 and 109/3/8 oats there appears to be transgressive segregation, to judge from the Swedish field results at least. The origin of the *ex* 109/1 series is too obscure to be considered in this respect.

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THE NITROGEN BALANCE OF LAYING HENS[1].

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(With Two Text-figures.)

Investigations concerning the protein nutrition of poultry appear mainly to have taken the form of feeding experiments in which growth or egg production have been compared on diets differing in the quality and quantity of protein which they contain. In view of the importance of protein in poultry nutrition, it is surprising that few accurately controlled nitrogen balance experiments are reported in the literature.

Ackerson, Blish and Mussehl (1, 2) in America have measured the endogenous loss of nitrogen by poultry by means of the balance experiment, and in this country Halnan (3) has reported the results of balance experiments carried out with laying and non-laying pullets. Halnan determined weekly nitrogen, calcium and phosphorus balances with two birds whose food intake was controlled. He found that both birds remained in positive nitrogen balance during the greater part of the fourteen weeks of the experiment, serious negative balances occurring only during the latter weeks when the birds were laying. His results indicate a marked storage of nitrogen during the week prior to the commencement of laying, this storage being maintained during the early stages of laying and falling off towards the end of the laying period. Halnan concluded that preliminary storage of nitrogen for egg production does not extend beyond a week or so prior to the commencement of egg laying, and that the nitrogen required for the purpose can be largely if not entirely supplied from the food given during the egg laying period.

The experiment here to be described was undertaken with a view to studying any variation which might occur in the daily retention of nitrogen by laying birds and in order to arrive at an estimate of the nitrogen requirement for egg production.

Experimental.

The birds used.

Two Rhode Island Red hens, which were in full lay, were selected for the purpose of the experiment. These birds had been reared on free range and subsequently kept semi-intensively on a good laying ration.

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Their egg record prior to the commencement of the experiment was as follows:

	1932			1933		
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar. (1–26)
Bird no. 1	1	0	1	4	8	15
Bird no. 2	4	15	19	20	9	15

The weights of the birds were as follows:

	Bird no. 1	Bird no. 2
At beginning of experiment	5 lb. 12¾ oz. *or* 2·629 kg.	5 lb. 9½ oz. *or* 2·537 kg.
At end of experiment	5 lb. 9½ oz. *or* 2·537 kg.	5 lb. 1 oz. *or* 2·297 kg.

Metabolism cages.

The birds were housed in wire cages 20 in. square which were 2 ft. high at the back and 2 ft. 3 in. high at the front, being provided with a sloping wire-mesh floor which extended 3 in. beyond the front of the cage, so that the egg, when laid, could roll out of the birds' reach. The cage and its floor were accommodated on a galvanised iron frame on four legs, beneath which was placed a white opalite glass plate for the collection of the excreta. An opening was provided in each of two sides of the cage to permit easy access to food and water in containers placed on the outside of the cage.

The food container was a glass cell fixed to the outside of the cage in such a manner that its top was in line with the bottom of the feeding opening, and screened on three of its sides by a celluloid sheet fixed inside it and extending to a height of 5 in. above it. It was thus impossible for the food to be contaminated with excreta or to be spilled outside the cage and only minimal amounts of food which had adhered to the birds' beak were spilled on to the plate beneath.

The experimental ration.

The ration used consisted of a mixture of bran, 10 parts by weight, wheat meal 50 parts, maize meal 30 parts and fish meal 9 parts. To this mixture 1 part of cod-liver oil was added to ensure adequacy of vitamins A and D, and 2·5 parts of ground chalk together with 1 part of common salt as a mineral supplement.

The ration was mixed by hand and sufficient was made up at one mixing to cover a period of three weeks. Immediately after mixing, the food was weighed in portions of 300 gm. in tared grease-proof paper bags, in order to overcome the difficulty of gravitational settling of the ingredients, which occurs during storage of a food mixture in bulk, and to ensure uniformity of composition of the daily rations presented to the birds.

The mixture was fed as an all-mash ration unaccompanied by either grain or grit.

Feeding and sampling technique.

The birds were fed 300 gm. of the ration each day at 9.30 a.m., the residual food being collected and weighed at the same time on the following day. Thus the daily food consumption was arrived at by difference. At the same time eggs were collected and weighed and the excreta collected and weighed in tared porcelain dishes. The drinking water, to which the birds had continual access, was changed each morning.

Immediately after weighing the excreta were transferred to a mortar, ground to a homogenous paste and duplicate samples withdrawn for determination of nitrogen.

Samples of the food were taken from the bulk immediately after mixing, and weekly composite samples were made up from samples drawn from the food residues left by the birds each day.

Analytical methods.

The total nitrogen content of the food and of the fresh excreta was determined by the Kjeldahl method.

The nitrogen content of the entire egg was determined as follows. A small hole was bored in either side of the egg and the shell contents were blown into a 500 c.c. pyrex Kjeldahl flask. The empty shell was then crushed into the neck of the flask and shaken down into the flask itself. The contents of the flask were then digested by boiling with nitrogen-free sulphuric acid together with potassium sulphate and copper sulphate. Considerable care was necessary in order to avoid excessive frothing, and usually 100 c.c. of acid were necessary to complete the digestion. The digest, after dilution with distilled water, was filtered through a Whatman No. 40 paper into a 1000 c.c. graduated flask, and the residual calcium sulphate, formed during the digestion, was washed with distilled water until free from acid, the washings being added to the filtrate. Filtrate and washings were then made up to the mark with distilled water and aliquots were taken for the determination of nitrogen by distillation with alkali in the usual manner.

The experiment commenced on March 27, 1933, after a preliminary period of seven days, and was continued for ten weeks.

DISCUSSION OF THE RESULTS OF THE BALANCE EXPERIMENT.

The results are presented in Tables I and II, which show the amounts of nitrogen consumed, voided in the excreta, and retained for egg production each day, together with the weight of each egg laid and its nitrogen content. The figures for nitrogen retained daily are the differences between nitrogen voided and that consumed daily. Although it is not strictly correct to balance nitrogen voided against nitrogen consumed during any one day, it is believed that no serious error is involved in this method of arriving at the daily nitrogen retention, since several investigations (4, 5, 6, 7, 8) have demonstrated that the rate of passage of the food through the alimentary canal of the fowl is relatively rapid.

Table I. *Bird I.*

Day	Nitrogen consumed gm.	Nitrogen voided gm.	Nitrogen retained gm.	Weight of egg gm.	Nitrogen in egg gm.
1	4·39	2·51	1·88	58·80	1·11
2	3·83	1·98	1·85	57·60	1·11
3	4·63	2·03	2·60	56·33	1·17
4	4·52	3·03	1·49	—	—
5	4·47	2·93	1·54	62·52	1·26
6	4·14	3·19	0·95	60·55	1·24
7	4·01	3·06	0·95	58·20	1·14
8	3·74	2·32	1·42	59·80	1·19
9	3·73	2·93	0·80	—	—
10	3·55	2·82	0·73	59·90	1·29
11	3·60	2·26	1·34	58·05	1·13
12	3·31	2·41	0·90	58·30	1·19
13	3·61	2·43	1·18	58·90	1·23
14	3·48	2·67	0·81	59·50	1·20
15	3·30	2·09	1·21	61·58	1·23
16	3·49	2·74	0·75	—	—
17	3·64	2·63	1·01	60·22	1·21
18	3·87	3·27	0·60	61·35	0·99
19	4·35	3·01	1·34	59·34	1·14
20	3·95	2·92	1·03	64·70	1·29
21	3·86	2·83	1·03	—	—
22	3·03	2·58	0·45	60·22	1·24
23	3·59	2·86	0·73	—	—
24	3·46	3·06	0·40	58·70	1·18
25	3·58	2·97	0·61	57·49	1·12
26	3·86	2·90	0·96	56·90	1·09
27	3·87	2·86	1·01	56·73	1·12
28	3·76	2·85	0·91	60·43	1·09
29	2·95	2·01	0·94	62·90	0·97
30	3·60	2·79	0·81	—	—
31	3·57	3·09	0·48	55·28	1·04
32	3·26	2·61	0·65	55·06	1·08
33	3·08	2·36	0·72	58·48	0·99
34	3·18	2·38	0·80	—	—
35	3·27	2·61	0·66	59·10	1·02
36	3·33	2·57	0·76	57·65	1·11
37	3·78	2·55	1·23	56·47	1·11

Table I (*cont.*).

Day	Nitrogen consumed gm.	Nitrogen voided gm.	Nitrogen retained gm.	Weight of egg gm.	Nitrogen in egg gm.
38	3·34	2·10	1·24	57·52	1·04
39	4·10	2·69	1·41	55·61	1·01
40	3·91	2·54	1·37	59·40	1·11
41	3·66	2·41	1·25	57·95	1·06
42	3·33	2·14	1·19	58·75	1·08
43	3·27	2·05	1·22	60·65	1·03
44	3·49	2·45	1·04	58·35	1·02
45	4·10	3·09	1·01	—	—
46	3·88	2·68	1·20	59·75	1·05
47	2·99	2·10	0·89	59·35	1·02
48	3·87	2·92	0·95	—	—
49	1·40	1·32	0·08	54·70	1·01
50	3·26	2·15	1·11	—	—
51	3·68	2·50	1·18	55·67	0·92
52	3·46	2·20	1·26	55·78	1·08
53	3·32	2·42	0·90	55·40	0·99
54	3·15	2·25	0·90	59·23	0·98
55	3·51	2·31	1·20	59·04	1·09
56	3·62	2·64	0·98		
57	2·77	1·94	0·83		
58	2·49	1·94	0·55	55·90	1·03
59	3·88	2·67	1·21	60·75	1·04
60	3·27	2·68	0·59	54·40	1·05
61	3·05	2·34	0·71	—	—
62	3·79	2·72	0·98	58·60	1·14
63	2·93	3·03	−0·10		
64	3·48	2·99	0·49		
65	2·93	2·63	0·30	55·30	1·14
66	3·72	2·63	1·09	54·35	0·96
67	3·39	2·67	0·72	55·20	1·11
68	3·06	2·19	0·87	—	—
69	3·95	2·66	1·29	58·30	1·09
70	3·03	2·43	0·60	55·90	1·03

Table II. *Bird II.*

Day	Nitrogen consumed gm.	Nitrogen voided gm.	Nitrogen retained gm.	Weight of egg gm.	Nitrogen in egg gm.
1	2·66	2·00	0·66	58·80	1·18
2	2·98	1·92	1·06	58·80	1·21
3	3·17	2·09	1·08	58·50	1·19
4	3·27	2·10	1·17	58·97	1·08
5	3·44	2·31	1·13	58·00	1·05
6	3·30	2·41	0·89	58·05	0·91
7	3·66	2·48	1·18	57·60	1·04
8	3·74	2·81	0·93	56·95	1·06
9	3·82	2·66	1·16	56·20	1·05
10	3·17	2·36	0·81	60·75	0·95
11	3·91	2·77	1·14	56·60	1·02
12	3·63	2·80	0·83	60·70	1·14
13	3·41	2·52	0·89	59·30	1·14
14	2·84	2·59	0·25	—	—
15	2·67	2·36	0·31	60·47	0·85
16	3·08	2·48	0·60		

Table II (*cont.*).

Day	Nitrogen consumed gm.	Nitrogen voided gm.	Nitrogen retained gm.	Weight of egg gm.	Nitrogen in egg gm.
17	2·66	2·47	0·19	62·10	1·13
18	3·19	2·32	0·87	58·34	0·80
19	3·41	2·66	0·75	56·92	1·05
20	2·94	2·63	0·31	55·22	0·98
21	3·59	1·52	2·07	63·40	1·06
22	3·92	2·65	1·27	60·76	1·06
23	3·47	2·64	0·83	—	—
24	2·91	2·47	0·44	56·36	1·02
25	3·28	2·65	0·63	57·50	1·07
26	3·44	2·46	0·98	60·04	1·08
27	3·33	2·43	0·90	54·69	1·03
28	3·54	2·60	0·94	56·06	1·06
29	3·31	2·28	1·03	58·74	1·08
30	3·91	3·37	0·54	—	—
31	3·19	2·52	0·67	—	—
32	2·75	2·23	0·52	57·25	0·85
33	3·27	2·51	0·76	57·31	1·08
34	3·30	2·43	0·87	—	—
35	3·73	2·65	1·08	54·70 55·45	0·97 1·00
36	3·44	2·56	0·88	53·17	0·98
37	3·50	2·45	1·05	56·35	0·95
38	2·76	2·01	0·75	56·90	0·95
39	4·10	2·25	1·85	—	—
40	3·10	2·32	0·78	63·07	0·97
41	2·91	2·16	0·75	56·12	0·96
42	3·29	2·27	1·02	53·85	0·95
43	3·22	2·01	1·21	53·05	0·94
44	3·06	2·13	0·93	53·72	0·95
45	3·67	2·66	1·01	53·63	0·91
46	2·74	1·73	1·01	57·79	0·94
47	3·63	2·40	1·23	56·92	0·95
48	3·72	2·53	1·19	57·55	0·98
49	2·76	2·09	0·67	57·16	1·02
50	3·24	2·19	1·05	56·95	0·98
51	3·38	2·15	1·23	—	—
52	2·80	2·12	0·68	59·85	0·87
53	3·16	2·28	0·88	60·10	0·85
54	3·58	2·47	1·11	55·64	0·96
55	3·27	2·16	1·11	53·14	0·91
56	3·30	2·19	1·11	52·60	0·91
57	3·01	1·92	1·09	53·90	0·91
58	2·11	1·75	0·36	55·26	1·03
59	3·69	2·52	1·17	58·06	0·96
60	3·44	2·25	1·19	57·82	1·03
61	3·08	2·12	0·96	—	—
62	3·22	2·48	0·74	58·10	0·99
63	2·78	2·05	0·73	53·80	0·98
64	2·73	1·88	0·85	54·90	0·91
65	2·92	2·03	0·89	53·07	0·98
66	3·04	2·11	0·93	52·65	0·98
67	2·95	1·96	0·99	50·85	0·91
68	2·45	1·75	0·70	59·10	1·04
69	2·93	2·12	0·81	—	—
70	2·09	1·77	0·32	54·60	0·99

Clearly, however, the nitrogen contained in an egg cannot be balanced against the nitrogen consumed during the day on which the egg was laid, since yolk formation and the passage of the yolk down the oviduct with the accompanying addition of albumen, shell membranes and shell, may occupy ten days or more. It is thus difficult to see how a valid daily balance between egg nitrogen and food nitrogen may be arrived at, and in the present experiment no attempt has been made to strike such a balance.

In the case of both birds, nitrogen consumption varied considerably from day to day, most of the figures lying between 3·0 and 4·0 gm. The daily consumption and retention of nitrogen are shown graphically in Figs. 1 and 2, in which days on which eggs were laid are distinguished by black dots. It will be seen that variation in nitrogen retention corresponds fairly closely with the variation in nitrogen consumption throughout the experiment. In this respect the results do not correspond with those obtained by Halnan in an experiment with pullets already referred to(3), in which, prior to the commencement of laying, the nitrogen retention increased with increasing nitrogen intake, whereas after laying had commenced the nitrogen retention decreased markedly despite a constant intake.

During the first ten days of the present experiment the nitrogen consumed daily by bird I fell off rather rapidly. Between the third and tenth day consumption fell from 4·63 to 3·55 gm. Further, it is to be noted that a consumption of more than 4·0 gm. of nitrogen, which was achieved on six of the first seven days of the experiment, only occurred on three subsequent occasions. Thus, at first sight, the initial fall in nitrogen consumption from values above 4·0 gm. daily (which by comparison with the remaining figures for bird I might be regarded as abnormal) to values below 4·0 gm., suggests that the bird had not become accustomed to the experimental conditions and therefore that a preliminary period of seven days is not sufficiently long. This suggestion, however, is not borne out by bird II whose nitrogen consumption during the first ten days gradually rose, the values being quite normal in comparison with the figures for the remainder of the experiment. Moreover, both birds' nitrogen retention is fairly well proportional to the nitrogen consumption which one would not expect to be the case if the birds were suffering a disturbance in metabolism due to being unaccustomed to the experimental conditions.

The nitrogen retention by both birds fluctuates considerably from day to day. The general trend of the figures in the case of bird I is in the

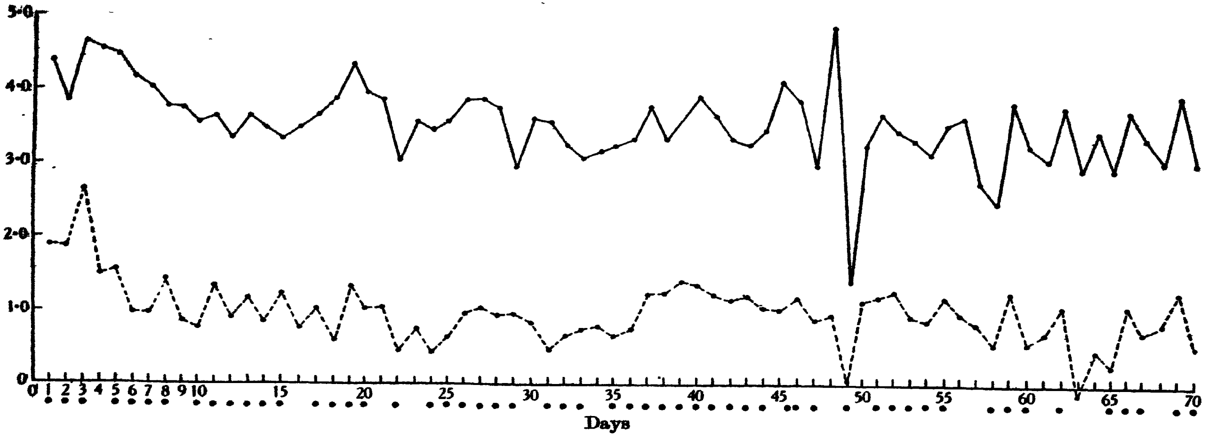

Fig. 1. Bird I.

Nitrogen consumed •—•—• Nitrogen retained •- - -•- - -•

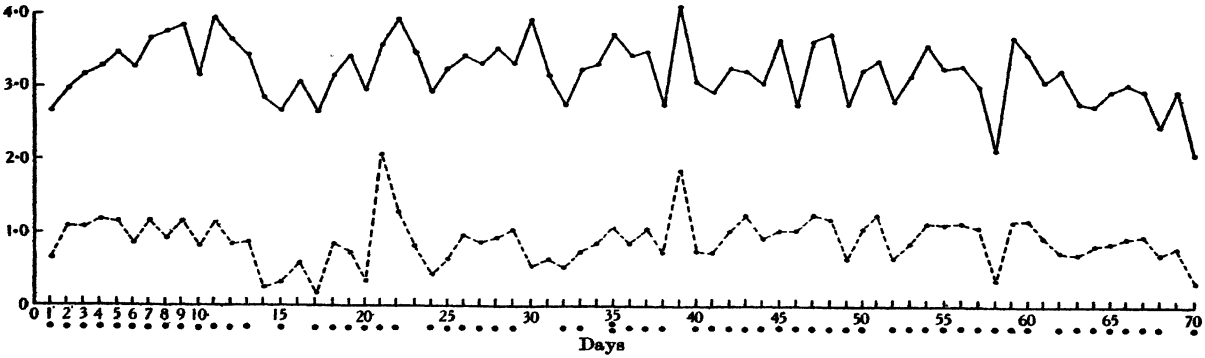

Fig. 2. Bird II.

direction of decreasing retention during the first four weeks of the experiment. During the next two weeks a tendency towards increasing retention is shown, followed by alternate decrease and increase during the remaining weeks of the period. The figures for bird II indicate a tendency towards decreasing retention during the first three weeks followed by gradually increasing retention during the next four weeks and a tendency to decrease during the last three weeks of the experiment. These variations, however, do not appear to be connected with the output of egg nitrogen or with the number of eggs laid in the various egg cycles. Further, there is no evidence of any marked storage of nitrogen during the laying period, such as was observed by Halnan with the non-laying pullet during the week immediately prior to the commencement of egg laying. On days when no eggs were laid the retention of nitrogen is rarely markedly different from that observed on days when eggs were laid. Thus it is evident that the storage of nitrogen which is manifested by birds immediately before they commence egg laying is not repeated during the laying period and the results suggest that during a period of heavy egg production, such as the present experimental period, synthesis of the nitrogenous constituents of the egg proceeds at a fairly uniform rate.

It is noteworthy that the total retention of nitrogen over the whole period is, in the case of both birds, greater than the total egg nitrogen produced, so that bird I stored 8·77 gm. and bird II 2·14 gm. of nitrogen. This is in accord with Halnan's findings in support of the view that the nitrogen for the purpose of egg production can be largely if not entirely drawn from the nitrogen consumed during the laying period.

Egg production was well maintained throughout the experiment, the eggs laid being of average size and good appearance and having a good shell texture. During the seventy days of the experiment bird I laid 54 eggs and bird II 61. It was therefore decided to make an estimate of the nitrogen requirement for the production of these eggs by the two birds, and to this end the digestibility of the nitrogen of the experimental ration was determined.

Determination of the digestibility of the nitrogen of the experimental ration.

Two Rhode Island Red laying birds were used for this purpose and were housed and fed as already described. The digestibility experiment was of fifteen days' duration after a preliminary period of fourteen days. Excreta were collected daily at the same time each day, and after weighing were transferred to Kilner jars and kept in the ice-chest. A few drops of toluene were added to each jar to minimise fermentation. Composite samples were drawn from the total excreta collected from each bird during the first three days and during each subsequent four days of the experiment. These samples were used for the determination of total nitrogen by the Kjeldahl method, uric acid nitrogen by the method of Woodman (9) and ammoniacal nitrogen by a method described by Halnan (10). The results are set out in Table III and refer to the fifteen-day period as a whole.

Table III.

	Nitrogen eaten gm.	Total nitrogen voided in excreta gm.	Ammoniacal nitrogen voided in excreta gm.	Uric acid nitrogen voided in excreta gm.
Bird A	39·656	31·091	2·364	18·147
Bird B	40·362	29·587	2·252	17·192

According to Katayama (11)

$$\text{Undigested nitrogen} = 102{\cdot}3\,\%\left\{\text{excretory nitrogen} - \frac{(\text{uric nitrogen} + \text{ammoniacal nitrogen}) \times 114{\cdot}6}{100}\right\}$$

Substituting the figures in Table III in the above equation one obtains 7·759 and 7·47 gm. as the values for undigested nitrogen for birds A and B respectively. Hence of 39·656 gm. nitrogen eaten by bird A, 31·897 gm. or 80·43 per cent. was digested, and of 40·362 gm. nitrogen eaten by bird B, 32·89 gm. or 81·48 per cent. was digested. The mean digestibility coefficients for the nitrogen of the experimental ration is therefore 80·95 per cent.

The utilisation of food nitrogen by birds I and II for maintenance and egg production.

During the course of the balance experiment bird I consumed 247·72 gm. of nitrogen and voided 179·59 gm. in her excreta. The total nitrogen content of the fifty-four eggs which she produced was 59·36 gm., so that her nitrogen balance over the whole experimental period was +8·77 gm. Assuming the food nitrogen to be digested to the extent of 80·95 per cent., the amount of nitrogen digested was 200·53 gm., of which 8·77 gm. were stored leaving 191·76 gm. as the amount of digestible nitrogen used by this bird for seventy days' maintenance and the production of fifty-four eggs.

Bird II consumed 224·96 gm. nitrogen and voided 161·99 gm. The total nitrogen content of the sixty-one eggs which she laid was 60·83 gm., and her nitrogen balance for the whole period was therefore +2·14 gm. The amount of food nitrogen digested was 182·11 gm., and since 2·14 gm. were stored 179·97 gm. of digestible nitrogen were used by bird II for seventy days' maintenance and the production of sixty-one eggs.

The utilisation of nitrogen for the purpose of egg production is obtained by subtracting the maintenance requirement of nitrogen from the results obtained above. Ackerson, Blish and Mussehl (12) have measured the endogenous nitrogen loss of non-moulting Rhode Island Red hens and found as a result of sixty trials that this loss averages 144 mg. per kg. of body weight. Now the average body weights of birds I and II during the experiment were 2·583 and 2·417 kg. respectively, so that their daily endogenous loss of nitrogen would be 372·0 and 348·0 mg. respectively. According to present day theory these figures represent the birds' daily maintenance requirement of nitrogen, and the requirements for seventy days' maintenance are thus 26·04 gm. for bird I and 24·36 gm. for bird II. Subtracting these figures from those already obtained for maintenance and egg production one obtains 165·72 gm. nitrogen as the amount utilised by bird I for the production of 59·36 gm. of egg nitrogen and 155·61 gm. nitrogen as the amount utilised by bird II for the production of 60·83 gm. of egg nitrogen. These figures amount to 2·79 and 2·55 gm. of nitrogen per gm. of egg nitrogen produced by birds I and II respectively and are in reasonable agreement with Halnan's tentative estimate of 15·0 gm. of digestible protein for the production of a 2 oz. egg (13). The figures are, however, overestimates of the production requirement of nitrogen, since they are arrived at by taking the endogenous nitrogen loss as the maintenance requirement of nitrogen, no account being taken of the necessary wastage of nitrogen consequent upon the utilisation of food protein of biological value of less than 100 for maintenance purposes. In the absence of information concerning the biological value of the proteins of the experimental ration for maintenance purposes, no closer approximation to the true production requirement of nitrogen can be made than that which is represented by the figures 2·79 and 2·55 gm. of digestible nitrogen per gm. of egg nitrogen.

The results of the present experiment suggest therefore that maintenance and egg production can be provided for by a less liberal feeding of digestible protein than the current feeding standards would imply. This becomes still more evident when the requirements for maintenance and the production of the eggs laid in the present experiment are calculated on the basis of current feeding standards and compared with the actual amounts of digestible nitrogen utilised. According to Halnan's tentative standards (13) bird I would require 229·51 gm. of digestible nitrogen for seventy days' maintenance and the production of fifty-four eggs. Actually 191·76 gm. digestible nitrogen were used by the bird. Again according to Halnan's standards bird II would require 243·83 gm. of digestible nitrogen for maintenance and egg production whereas she actually utilised 179·97 gm.

SUMMARY.

A nitrogen balance experiment of ten weeks' duration with two Rhode Island Red laying hens is described.

The observed variations in the retention of nitrogen for egg-producing purposes do not appear to be connected with the output of egg nitrogen or with the number of eggs laid in the various egg cycles.

The view held by other workers that the nitrogen required for egg production can be largely if not entirely drawn from the food supplied during the laying period is confirmed.

The marked storage of nitrogen which has been shown to occur immediately prior to the commencement of egg laying is not repeated during the laying period, and it is suggested that during a period of heavy egg production synthesis of the nitrogenous constituents of the egg proceeds at a fairly uniform rate.

An estimate is made of the digestible nitrogen used by the birds during the experiment for maintenance and production purposes and it is suggested that maintenance and production can be provided for by a less liberal feeding of digestible protein than current tentative feeding standards would imply.

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